EVALUATION OF THE EFFECTS OF PRE-DRYING TREATMENTS AND DRYING METHODS ON THE DRYING KINETICS AND QUALITY OF TOMMY ATKIN MANGO SLICES

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DISCLAIMER

As the candidate’s supervisors, we have approved this thesis for submission

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ABSTRACT

Mango is a perishable fruit, harvested once a year during the summer season. Smallholder farmers growing mango experience relatively high post-harvest losses because they receive large volumes of produce at the same time. Drying is a preservation method proven second to cooling in performance. In South Africa, dried mango fetches higher returns compared to canned mango, and mango juice, atchar and jam. Open-Air solar Drying (OAD) is a popular drying method used for producing dried mango. However, this method of drying has setbacks resulting in produce quality loss. Convective Oven Drying (OVD) is a more efficient drying method, however, it has high-energy consumption. In South Africa, there is lack of research on hot-air drying methods, as well as their performance when drying mango fruit. With the current shift in use of renewable energy for drying operations, research is focusing on improving solar drying technologies. These include increasing the drying capacity and reducing the drying time through modifying a greenhouse. Considering the research gap in South Africa on drying technologies and the limitations of open-air solar drying, this study comparatively assessed the performance of three drying methods, namely, (a) Convective Oven Drying (OVD), (b) Open-Air solar drying (OAD) and (c) a Modified Ventilation Solar Drying (MVD). OVD was carried out at a set temperature of 70˚C, OAD and MVD at ambient temperature of 15.55˚C -36.77˚C, at an RH of 22.96%-79% and solar radiation of 317W.m^{-2}- 1016 W.m^{-2}. The MVD improved the ambient conditions to obtain an average maximum temperature of 64.26 ˚C and RH of 17.6%. The drying time was longer for mango slices dried in OAD, MVD and OVD, respectively. The lemon juice pre-treatment did not affect the drying time. The drying time was reduced for 3 mm, as compared to the 6 mm and 9 mm dried mango slices, due to the relatively high drying rates. Drying took place in the falling drying rate period for most mango samples, indicating that diffusion was the driving mechanism in the drying experiments. The effect of the drying methods on the drying kinetics of mango slices (3 mm, 6 mm and 9 mm) as well as the effect of lemon juice pre-treatment was investigated. Non-linear regression analysis was used to assess the empirical model that best fits the experimental moisture ratio data. The quality parameters that were evaluated included the colour, rehydration, sensory properties, changes in mango microstructure and microbial changes. The empirical model that was best fit for the drying data was that of the Midilli *et al.*, followed by Page model because a higher R^2, a lower root mean square (RMSE) and a lower chi-square (X^2) was obtained from non-linear regression analysis. A quality analysis indicated that colour change (ΔE) was not significantly

(P>0.05) affected by pre-treatment, although control samples that were dried in the OAD had a relatively higher colour change, resulting to browning. The rehydration ratio and electronic microscopy (SEM) showed structural changes in dried samples, with thicker mango slices having a relatively lower rehydration ratio, and the SEM scans dominated by cracks and pores, which were much more visible for 9 mm mango slices. Sensory evaluation results indicated that the panellists preferred the flavour and colour of pre-treated 3 mm mango slices compared to thicker control and pre-treated dried mango slices. In addition, the overall acceptability of dried mango was relatively higher for MVD-dried, than OVD- and OAD-dried mango slices, respectively. The fungi and anaerobic bacteria levels found in dried mango slices were higher than the recommended levels of $1\text{x}10^{3}$; however, there were no pathogenic microbes detected in the fresh and dried samples. The study findings show that dried mango is an acceptable produce to consumers, especially in areas like Kwazulu-Natal, were mango is scarce. MVD is a drying method, which is practical and can solve the shortcomings of OAD. This method is a renewable energy alternative to OVD and further improvement is required to increase temperature and ventilation is necessary to reduce drying time.

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1. INTRODUCTION

Fruits and vegetables contain vitamins, minerals, dietary fibre, phytochemicals and antioxidants (Pereira, 2014; Conner *et al.*, 2017). Therefore, they are an abundant source of nutrients in a healthy human diet (Conner *et al.*, 2017). According to the World Health Organisation (WHO), approximately 16 million disability-adjusted lives (DALYs) and 1.7 million of deaths worldwide is caused by low fruits and vegetable consumption (WHO, 2011; Mujcic, 2016). In 2000 alone, about 23.6 million of the world's population did not consume enough fruits and vegetables (Lock *et al.*, 2005). Research studies indicate that the consumption of sufficient fruits and vegetables as part of a balanced diet, helps to reduce the risk of major non-communicable diseases, such as cardiovascular disease and certain cancers. An awareness of the reduced health risks associated with the consumption of fruits and vegetables has led to a rise in the demand for fruits, including mangoes, bananas, pineapples and passion fruit (Joosten *et al*., 2015).

Mango (*Mangiferia Indica L.)*, a tropical and subtropical fruits, has the highest per capita consumption in the world and it comprises about 39% of the total production of subtropical fruits. Its production in South Africa has been increasing over the years. In the 2014/2015 production season, the highest production of 70 400 tons was recorded, compared to the five preceding years (Ntshangase *et al.*, 2017). The Limpopo Province of South Africa produces 75% of this fruit and it is planted over an area of approximately 5 013 hectares (Mashau *et al.,* 2012; DAFF, 2016). The increasing popularity of the mango fruit is, attributed to its excellent flavour, attractive fragrance, beautiful colour, taste and nutritional properties (DAFF, 2016). The gross value of the mango fruit increases because of its processed products, such as canned mango, juice, atchar, jam and dried mango. Dried mango is the product with the highest value (Schiavone *et al.*, 2013). Besides its favourable qualities, mango is a highly perishable fruit because of its high moisture content (>80%), which results in a short shelf-life (<16 days) (Tettey, 2008). Furthermore, Mangoes have a short harvest season, which makes them fetch high prices during off-seasons (Bretch and Yahia, 2009). According to Sarkar *et al*., (2011) the perishable nature of mangoes contributes to relatively high post-harvest losses of the fruit. These losses have been estimated to be approximately 40-50% in developing countries, including South Africa (Kitinoja and Alhassan, 2012; Mashau *et al.*, 2012). Improper handling and the lack of suitable storage of the fruit cause the losses after harvest (Sarkar *et al.*, 2011; Maremera, 2014). Improper handling and the lack of storage leads to wilting, shrivelling, chilling injury and decay, due to fungi and bacteria, as well as physical and mechanical injury problems (Mashau *et al.*, 2012). Considering the increased value of mango during off-season, drying of mangoes can potentially solve the challenge of post-harvest losses of fresh mango and fetch high prices, to improve the livelihood of smallholder farmers.

Smallholder farmers in developing countries, including South Africa are able to produce 80% of the fruits and vegetables, including mango (Murthy, 2009). However, they cannot rely on agriculture as a livelihood strategy. This is primarily because of the post-harvest losses experienced before the fresh produce reaches the consumer. Reducing the post-harvest losses of fresh produce is an important part of sustainable agricultural efforts that aim to increase food availability (Kader, 2005; Sarkar *et al.*, 2011). This involves the development of technologies for the preservation of fruits and vegetables to manipulate storage temperature and relative humidity (cooling), efficient packaging technologies, canning and drying. The drying technologies perform better than canning and it is second to cooling in performance (Alamu *et al.*, 2010).

Fruits are dried to extend the shelf-life and improve their market value, considering their perishable nature this could increase the availability of perishable commodities, which are also seasonal in nature (Aghabashlo *et al.*, 2013). Drying is a heat and mass transfer process wherein there is a transfer of water, by diffusion, from inside the food material to the air-food interface and from the air-food interface to the outside air, simultaneously, by convection (Afzal and Abe, 2000; Belessiotis and Deylanni, 2010; Schiavone, 2013; Demiray and Tulek, 2014; Süfer *et al.*, 2016). Heat is applied to remove moisture from agricultural products. Heated air increases the capacity for water vapour absorption (Afzal and Abe, 2000; Blanco-Cano *et al.,* 2013; Aghabashlo *et al.*, 2013). Research studies have found that a reduction of the moisture content of food, to 10-20% prevents bacteria, fungi and enzymes from spoiling the food. In addition, it reduces the microbial deterioration of fruits and vegetables and reduces contamination by pathogenic microbes (Sivasankar, 2009; Tsado *et al.*, 2015; Ntuli *et al.*, 2017).

Drying is the most cost-effective way of preserving fruits and vegetables, and hot air is the common drying medium (Jangam *et al*., 2010). Convective hot air drying methods, such as oven drying, are efficient and used for both small- and large-scale drying operations. However, convective drying methods rate as one of the energy-intensive methods, competing with distillation, with high levels of energy consumption. This is caused by the use of hot air at relatively high temperatures, which can reach 70°C (Jangam *et al*., 2010). As a result, several countries have found that the energy consumption of conventional drying systems ranging from 10-25% of the industrial energy consumption (Jangam *et al*., 2010; Tchaya *et al*., 2014). These are not feasible drying technology solutions for smallholder farmers of South Africa because there is scarcity of electricity and relatively high electricity tariffs (Hoffman and Ashwell, 2001; Gets and Mhlanga, 2013; Pretorius and le Cordeur, 2016).

Open-air uncontrolled solar drying is commonly used for drying fruits, such as mango in both the small- and large-scale drying operations of South Africa (Sulaiman and Inambao, 2010; Kivevele and Huan, 2013). Open-air uncontrolled solar drying is an uncontrolled process in which the produce is exposed to direct sunlight, rain and dust. Produce that is dried, using open-air uncontrolled solar drying is undesirable because the drying method causes variability in product quality (Madhlopa *et al*., 2002; Pangavhane and Sawhney, 2002, Sagar and Kumar, 2010). Industrial operations use conventional methods, such as oven drying and fluidised bed drying. Other alternative methods to hot air drying are vacuum drying, microwave drying and freeze-drying. Improved solar drying generates relatively high temperatures, has a low relative humidity, a short drying period and is relatively inexpensive. In addition, research shows that an enhanced solar dryer shortens the drying time by 65%, when compared to open-air uncontrolled solar drying and it produces uniform quality fruits/vegetable when compared to open-air uncontrolled solar drying (Wankhade *et al*., 2014). Hence, the use of improved solar drying technology to reduce the energy costs and to speed up drying is an attractive option.

Considering that the majority of South African provinces receive an average of 5.5 $kWh.m^{-2}$ of solar irradiation, the use of solar energy as a source of energy is feasible in the country (Fluri, 2009). However, extensive research needs to be undertaken on the utilization of solar energy in the South African food industry. This will ensure the preservation of perishable produce, such as mangoes. Several research studies have developed efficient solar drying technologies and they include improvements on the efficiency of the indirect mode of drying. This usually involves integration of innovative aspects, such as solar chimneys, the use of thermal storage and wind ventilators. Naturally, ventilated dryers require no electrical or mechanical components, because the driving force is a result of the temperature difference or changes in air density (Schiavone *et al*., 2013). There is a research gap in South Africa, with limited investigations into smallholder farmers who produce mangoes and who are not aware of this value-adding technology, which could assist in improving the marketability of their produce. This is because there is a lack of research for the improvement of solar drying technologies.

This study has identified a need for investigating an innovative solar dryer that uses solar energy to preserve the mango fruit, and to reduce the post-harvest losses experienced by mango-producing farmers in the Limpopo Province. The aim of this study is, to evaluate, comparatively the effect of hot air methods on drying characteristics and quality of Tommy Atkin mangoes. This could result in the reduction of post-harvest losses and it could increase the shelf-life of fresh produce, simultaneously creating employment, providing food security and improving the livelihoods of the smallholder farmers in South Africa. This would be an innovative design because it would incorporate a wind ventilator, to improve the ventilation during drying. Another aim of this project is to evaluate the performance of a naturally-ventilated direct solar drier with a wind ventilator. The specific objectives are:

(i) to evaluate and assess performance of the improved solar dryer in terms of variation in the relative humidity and drying temperature during the drying process;
(ii) to determine the empirical model which best describes the drying process; and
(iii) to determine the physical and chemical quality of dried mango.

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2. LITERATURE REVIEW

The literature review section includes an overview of the mango fruit, highlighting its importance, the post-harvest losses and current preservation technologies. A review of the basic underlying principles of drying, factors influencing drying and the common drying methods are included in this section. This chapter also includes solar drying methods and the practices used to enhance solar dryer performance. Furthermore, this review includes the methods of analysis for assessing the quality properties and drying models.

2.1 Production of The Mango Fruit

Mango (*Mangiferia indica* L.*)* is a delicate and tasty fruit grown in tropical and subtropical regions of the world. The mango fruit constitutes for nearly half of the worldwide production of tropical and subtropical fruit and it originated in the Indi-Burmese region (Ravindra and Goswami, 2013). Mangoes are produced commercially in more than 87 countries, with India having the highest production of 13.5 million tons per annum, which accounts for approximately 50% of the fruit (van Deventer, 2011). Other major producing countries are China, Indonesia, the Philippines, Pakistan and Mexico. In South Africa, mangoes are the third most important subtropical fruit, after citrus and banana. Tommy Atkins mango cultivars are mainly grown in the subtropical regions of Limpopo (Hoederspruit, Levubu and Tzaneen) and Mpumalanga (Kiepersol, Malelane and Nelspruit) (Ntombela and Moobi, 2013). Only 0.22% of the locally-produced mango fruit is exported. Therefore, most of the product is consumed locally (Ntombela and Moobi, 2013).

The production of dried mango has been increasing over the years and due to the increased awareness of its nutritional benefits, the value is higher than that of atchar. According to Mudau *et al*. (2012), there has been a lifestyle change of South African consumers, with fatty foods becoming unpopular, and this has been the major influence in the boost of the fruit-drying business. This provides an opportunity for mango-producing smallholder farmers, to penetrate the industry by producing dried mango. This allows them to sell mango fruit during the off-season, which promotes higher returns and results in the improvement of their livelihoods.

2.2 Post-harvest Losses of Fruits and Vegetables

Fruits and vegetables are regarded as a delicate commodity and approximately 1.3 billion tons, produced for human consumption are estimated to be lost globally (Oelofse and Nahman, 2009; Prusky, 2011). Developing countries experience major losses in the field (Parfitt *et al.*, 2010). Kitinoja and Alhassan (2012) describe post-harvest losses as that portion of the fruits and vegetables that are produced and do not reach the consumers. The highest losses are reported for fruits and vegetables, root crops and tubers (Gustavsson *et al.*, 2011). Research done by Oelofse and Nahman (2009) substantiates this because fruits and vegetables combined, with root crops and tubers contribute to 57% of the overall waste stream, as highlighted in Figure 2.1.

According to Munhuweyi (2012), the top global fruits and vegetable producers air India, China and Japan, respectively. However, these countries experience a considerable amount of post-harvest losses annually. The post-harvest losses in India can meet the annual fresh produce needs of the UK (Reddy, 2000). Regions in the world experience about 20% post-harvest losses and the highest losses (45-50%) have been reported in Africa and Asia, respectively (Kitinoja and Kader, 2003; Gustavsson *et al.*, 2011). In Nigeria, post-harvest losses experienced by smallholder farmers can reach about 20-60% for fruits and vegetables, such as tomato, okra, onion, mango and carrot (Folayana, 2013). These figures coincide with the 50% of loss of mangoes, bananas, oranges and pawpaws, by smallholder farmers and street vendors in the Limpopo Province of South Africa (Mashau *et al*. 2012).

Post-harvest losses in South Africa are due to the low level of post-harvest technology, which causes a loss in produce quality and variations in the compliance standards (Mashau *et al.* 2012). External factors include mechanical injury, physical factors and microbial deterioration, and internal factors include physiological deterioration. The loss of fruits and vegetables aggravates hunger as less food becomes available for consumption (FAO, 2009). This therefore presents a challenge to the food industry to ensure that the food demand of the growing population is met, which must considering that the South African population is estimated to have an annual increase of 2%, with projections indicating that there will be 82 million people by 2035 (STATSSA, 2013). It is therefore vital to reduce post-harvest losses by preservation of fruits and vegetables, such as mangoes as a complementary alternative for improving agricultural productivity.

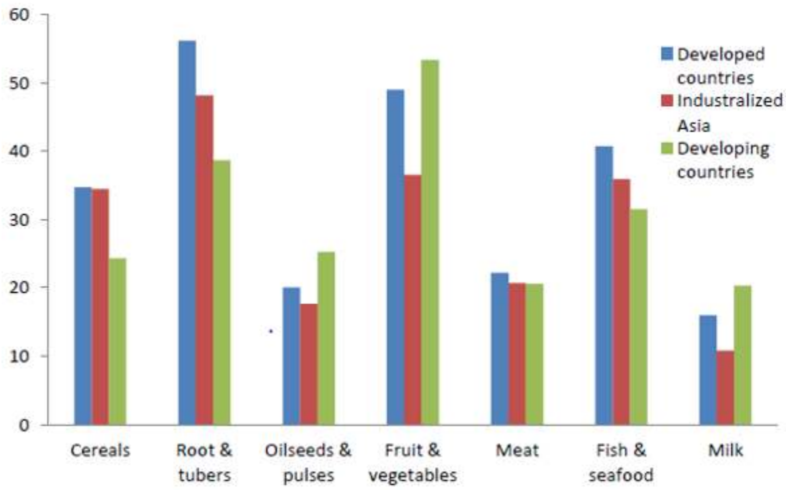

Figure 2.1 Food Losses variation across countries (after Gustavsson *et al*., 2011)

2.2.1 Causes of postharvest losses

Post-harvest losses experienced by smallholder farmers are caused by external factors (mechanical injury or physical damage and microbial deterioration) and internal factors (physiological). According to Munhuweyi (2012), the above causes complement each other. The pre-dominant form of mechanical injury is bruising, which makes the produce susceptible to microbial spoilage (Bollen, 2006; Salami *et al*., 2010). Furthermore, the presence of injuries, such as bruises increases the rate of water loss and respiration, resulting in physiological deterioration, which increases the rate of respiration and water loss in a produce. The changes that occur during respiration and water loss may result in wilting, sprouting, and increasing product susceptibility to mechanical damage (Maremera, 2014).

Physical/environmental conditions, such as high temperature and relative humidity create favourable conditions for micro-organisms to grow. Physiological deterioration is, also caused, by the high temperatures, above 30°C , experienced in the Limpopo Province, because of high respiration rate and water activity of farm produce (Maremera, 2014). Jangam *et al.* (2010) substantiated this by indicating that the rate of fresh produce deterioration increases two-to three-fold, for every 10˚C increase in temperature. Micro-organisms, fungi, yeasts and moulds and bacteria, find conditions of high temperature, moisture, damaged produce and water activity conducive for survival. In addition, the yeasts and moulds contaminate food with diseases and parasites, which causes spoilage (Kitinoja and Kader, 2003; Munhuweyi, 2012; Folayana, 2013).

Therefore, the drying of fruits and vegetables immediately after harvest eliminates the need for creating a conducive environment for maintaining product quality, because the reduction of water activity to less than 60% also reduces the chance of product infestation by micro-organisms, mechanical damage and physiological deterioration (Kader, 2005; Maremera, 2014). Table 2.1 summarises and highlights the most common primary and secondary causes of post-harvest losses.

Table 2.1 Summary of the factors causing post-harvest losses

Category	**Features**	**Primary Causes**	**Secondary Causes**	**References**
Mechanical Injury	Bruising, cutting, breaking and impact wounds	Vibrations, Compression and impact damage.	Unsuitable packaging, poor handling of produce before and during transportation.	Kitinoja and Kader (2003); Salami *et al.*, (2010); Munhuweyi, (2012).
Physical Factors	Softening and premature ripening	Temperature and relative humidity	Respiration rate Water activity	Mashau *et al.* (2012); Kader (2005).
Microbial Deterioration	Discoloration, rotting and black spots	Bacteria, Fungi, Insects and moulds.	Diseases and Parasites	Jangam *et al.* (2010); Salami *et al*. (2010); Munhuweyi (2010).
Physiological Deterioration	Undersize fruit and deformation	Metabolism, growth and water loss	Respiration, ethylene production	Folayana (2013); Maremera (2014).

2.3 Fruit Preservation Methods

Preservation technologies improve food security, by reducing post-harvest losses, to ensure food availability. Cooling, canning, efficient packaging technologies and drying are technologies used for the preservation of fruit. Cooling is a relatively expensive method and it is unaffordable for smallholder farmers, mainly due to the high-energy requirements to run the compressor. According to Mohammed (2004), canning requires more work and its energy requirements are higher than that of cooling. Furthermore, there is a growing resistance, to the use of chemicals for food preservation and energy intensive technologies and this has led to a renewed interest in drying.

This simultaneous heat and mass transfer process takes place simultaneously to modify the physical and microstructure of fruit (Belessiotis and Delyannis, 2010; Mkhathini, 2014). Drying decreases the water content in fruit, this inhibits the development of the micro-organisms and lessens the microbial and physiological deterioration process, hence ensuring product stability (Pavan, 2010). Research indicates that variables, such as the produce colour, texture, shape, size, porosity, density and shrinkage are affected during drying. This study intends to elucidate the variables that cause major changes during heat and mass transfer processes, when drying mangoes.

2.4 A Review of Drying Principles and Factors Controlling the Drying Process

2.4.1 Drying principles

Drying is the evaporation of moisture from a crop. It is described as the simultaneous heat and mass transfer process. Drying reduces the moisture content of mangoes from 80-85% to 12-18% (Schiavone, 2011). According to Correa-Hernando *et al*. (2011), the energy consumed during drying occurs during the evaporation of liquid water to vapour. This ranges between 0.43 -20.35 $MJ.kg^{-1}$ and research indicates that the amount of energy required for drying of mangoes is 1.564 $MJ.kg^{-1}$. The amount of heat required for drying is equal to the latent heat of the vaporisation of water, which is 2260 $kJ.kg^{-1}$ (Leon, 2002; Schiavone, 2011). During drying, water from the produce surface evaporates first and then migrates from within the crop, as the crop absorbs the additional heat (Schiavone, 2011). Schiavone (2011), describe these two processes as the constant and falling rate stages of drying, as shown in Figure 2.2. The driving mechanisms in the drying processes include surface diffusion, liquid/vapour diffusion and capillary action within the porous region of foods (Erbay and Icer, 2010). Several research studies have reported that the moisture removal from fruit is dominated, by diffusion (Doymaz, 2007, Duc *et al.*, 2011; Hashim *et al.*, 2014).

Diffusion happens, when drying occurs in the falling rate period. Furthermore, fruit-drying process is in the falling rate period and sometimes has a slight constant rate period during initial stages of drying. The observations of a falling rate period during drying, were made in the drying of kiwi, lemon fruit and mango (Darvishi *et al.*, 2013; Akoy, 2014). Serement *et al.* (2015) observed a constant rate for the first 5-10 minutes followed by a falling rate in drying of pumpkin. The process of drying ends when the moisture vapour pressure within the product is equivalent to the pressure of atmospheric moisture (Erbay and Icer, 2010). This is called the equilibrium state, where the moisture content of the wet material is in equilibrium with the surrounding air, at a given relative humidity and temperature. Studies indicate that only the physically held water is removed during the drying process. Equations 2.1 and 2.2, indicate the moisture loss during the constant and falling drying rate periods, respectively.

$$\frac{m(t) - m_c}{m_i - m_c} = \exp(-kt_c) \tag{2.1}$$

$$\frac{m(t) - m_E}{m_C - m_E} = \exp(-kt_c) \tag{2.2}$$

Where, m (t) (%) is the dry basis moisture content at any time, m_c (%) is the moisture content at the end of the constant rate drying period, m_i (%) is the initial moisture constant, m_E (%) is the equilibrium moisture content, k (dimensionless) is the drying rate constant per minute and t_c (min) is the drying time it takes to reach the constant rate period.

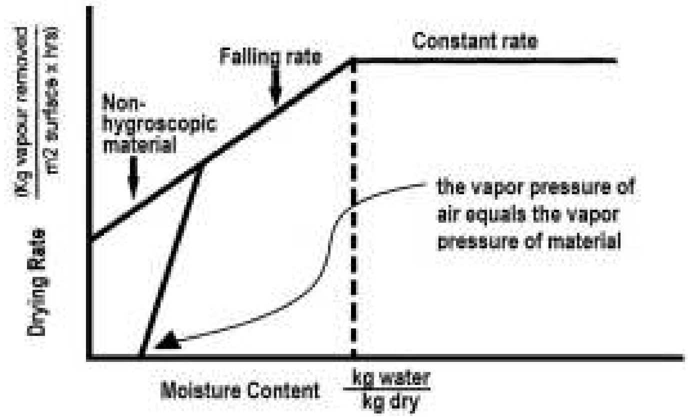

Figure 2.2 Drying rate curve (after Schiavone, 2011)

Psychometry

According to Schiavone (2011), ambient air is assumed to have a dry bulb temperature, as in Point One of Figure 2.3. As the ambient air is heated during drying, the relative humidity of the air remains constant until reaching the heated temperature, as in Point Two, where the humidity is reduced. Point 2-3 illustrate the removal moisture from the produce. The relative humidity increases, whilst the temperature reduces, because the drying air fills with water, which has evaporated from the crop. The air is reaching saturation at Point 3. The enthalpy remains constant during drying.

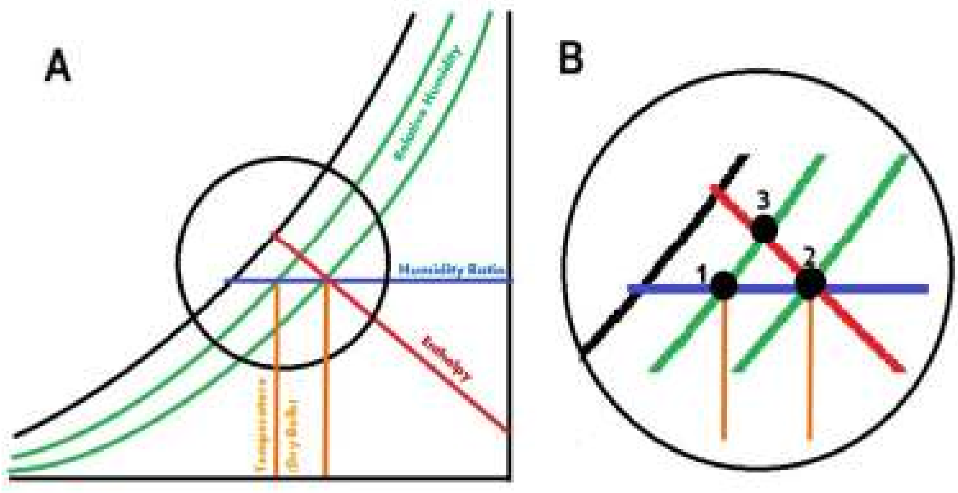

Figure 2.3 Psychometric chart showing the drying process (after Schiavone, 2011)

Water activity

Every food and agricultural product has a limit below which micro-organisms stop growing. The control of water activity of fruit is essential to minimize microbial deterioration of fruit (Sivasankar, 2009; Belessiotis and Delyannis, 2010). According to Jangam and Mujumdar (2010), the water activity influences the quality, safety, shelf-life, texture and flavour of food. The water activity is equal to the relative humidity of the surrounding air.

$$\alpha_W = \frac{RH}{100} \tag{2.3}$$

Where, α_W (dimensionless) is the water activity, RH (%) is the relative humidity, as shown in Equation 2.3 (Sivasankar, 2009). According to Sivasankar (2009), bacteria growth is at α_W = 0.85, mould and yeast α_W = 0.61, fungi is at $\alpha_W < 0.70$. Therefore, it is of vital importance for dried fruit to have water activity levels that will not allow for micro-organism to growth.

2.4.2 Climatic factors influencing the drying process

Relative humidity and temperature are reported to be the major factors influencing the rate of evaporation during the constant and falling rate periods of drying. Therefore, this study seeks to consider these factors, to establish their influence in the drying process.

Drying temperature

The greater the drying temperature difference between the food and the heating medium, the greater the rate of heat transfer during drying. In hot air drying the higher air temperature holds more moisture before reaching saturation, therefore the drying rates are relatively higher (Sivasankar, 2009). An average temperature of 60°C is suggested for the drying of fruit such as mangoes. A temperature of 65°C, compared to 55°C, is also optimal for drying of mangoes, because it reduces the drying time from 210 min to 180 min (Goyal *et al.*, 2006). Some researchers suggest a progressive temperature rise and others suggest an initial high temperature (Rahman, 2007; Jangam *et al.*, 2010).

High temperature increases the drying rate by increasing the ability of air to hold moisture, therefore driving moisture to the surface rapidly. However, high temperatures above 80°C affect the colour and texture of the fruit, depending on the thermal sensitivity of the fresh produce (Leon *et al.,* 2002). According to Abdullahi *et al.* (2013), a relatively low temperature at the beginning of drying causes product infestation by micro-organisms, before the produce is adequately dried. A temperature below 55℃ is suggested at the end of the drying process, to prevent the browning of produce (Schiavone, 2011). Therefore, elevated temperatures along, with increased airflow rates and reduced levels of relative humidity permit higher drying rates. Schiavone (2011) and Leon *et al*. (2002) indicated that these conditions only apply, if diffusion is the controlling process in water removal. Where there is a lower moisture content, the airflow rate is less important than the temperature. In this case, higher temperatures lead to a higher drying rate during the falling rate of the drying curve, as shown in Figure 2.2.

Relative humidity

This is the driving force for moisture transfer. As the temperature increases, the relative humidity decreases and the rate of drying increases (Huff, 2008; Jangam *et al.*, 2010). Air with a relative humidity of approximately 40% is preferred during drying (Rahman, 2007). Kaya *et al*. (2007) investigated drying parameters, with a relative humidity of 40%, 50% and 70%. It was found that a decrease in relative humidity, with an increase in temperature and velocity, increases the diffusivity coefficient. Heating air increases the ability of air to hold moisture. According to Leon *et al.* (2002), this increases the thermal efficiency of the drying process.

2.5 Drying Methods

There are several types of dryers that are used for drying fruit. This study focuses on, hot air drying, microwave drying, freeze-drying and vacuum drying.

2.5.1 Hot-air drying

This is the one of the common methods of drying, where heated air is circulated by natural or forced ventilation through the moisture-filled product. It is used for drying piece-form fruits (Dirkbarsan, 2010). The operation temperatures range from ambient to 100℃ and electricity, solar or geothermal, are used as energy sources (Surat and Thorat, 2010). Research studies indicate that two- and four-stage hot-air drying is recommended, because it increases the drying rate by approximately 24%. This also improves the product quality (Surat and Thorat, 2010). Hot-air drying methods includes, kiln dryers, fluidized bed dryers, cabinet tray dryers, tunnel dryers, pneumatic dryers, spray dryers and rotary dryers. Three hot air drying methods, namely, open-air solar drying, oven drying and modified solar drying using a tunnel/greenhouse dryer will be implemented, because of their popular use and applicability, with a cheaper energy source, such as solar energy.

2.5.2 Freeze-drying

This is a two-stage process, which involves, firstly, freezing of the water in the food materials and then application of heat, so that the ice can be directly converted to vapour. A partial vacuum is created to allow for sublimation of ice. Freezing is done at temperatures of between -50°C and -80°C , while the heating temperatures can range between 10–50°C (Surat and Thorat, 2010). Literature studies indicate that this method has preference, because it retains the product's structure. However, its application is limited for small-scale operations, as it is relatively expensive. Therefore, freeze-drying was not considered for this study, because the purpose is to create a solution that will be affordable for small-scale farmers producing a relatively large amount of produce and that is simple to use.

2.5.3 Microwave drying

Feng *et al.* (2012) described microwave drying, as the exposure of produce to high frequency electromagnetic waves. The frequency range is from 300 MHz to 300 GHz, with a wavelength of 1 mm-1 m. The dielectric heating of produce results in rapid energy coupling into the water, leading to fast heating and drying (Dirkbarsan, 2007; Feng e*t al.*, 2012). The main advantage of microwave drying is that it reduces the drying time four to eight times, compared to other drying methods. This is because the product loses internal water faster. However, there is a limit to the use of microwave drying, as it heats produce non-uniformly. Therefore, microwave drying is used to enhance other drying methods, such as hot-air drying. In addition, microwave-assisted vacuum drying is reported to be one of the most successful applications in food drying operations (Feng e*t al.*, 2012). However, the cost is relatively high and the magnetron has a short lifespan. In addition, the adaptability of this technology is limited by a lack of understanding of the operation. This study did not adopt microwave drying because it has a relatively high capital and running cost for purchasing magnetron.

2.5.4 Vacuum drying

Vacuum drying is used for drying heat-sensitive fruit and vegetable. The process is done at a pressure less than 100 kPa, at different temperatures (Surat and Thorat, 2010). According to Cheenkachorn (2007), creating a vacuum in the dryer causes a lower boiling point, so that water can evaporate at a low temperature. A lower drying temperature causes a lower rate of oxidation, which results in an improvement of produce quality. This method, however, requires high capital and operational costs, to ensure that the pumping system for the vacuum runs smoothly. Therefore, it was not considered as a solution for this study, because it is relatively expensive and requires the control of pressure and temperature. Furthermore, the operation of the vacuum dryer requires certain specialised operating skills.

2.6 Classification of Solar Dryers

Solar dryers transfer the radiation, either directly or indirectly, to the product. This section reviews the two different classes of solar dryers, based on how the produce receives radiation.

2.6.1 Open-air uncontrolled solar drying

Open-air uncontrolled solar drying is a common preservation method used for agricultural products in tropical and subtropical countries. It is usually applied where outdoor temperatures are usually 30°C or higher (Akarslan, 2012; Paul and Singh, 2013). The crop is spread out in open sunlight on the ground, on floors or roofs and is usually turned once or twice daily (Jairaj *et al*., 2009; Paul and Singh, 2013). The solar radiation that is absorbed in the crop converts it, to thermal energy. The increase in the temperature results in moisture evaporation from the crop, which causes the drying, as shown Figure 2.4.

According to Hossain *et al.* (2007), the drying rate in open-air uncontrolled solar drying is a relatively low and this increases the drying time. Pangavhane and Sawhney (2002) showed that pre-treated grapes require nine to ten days, while, Mercer (2012) took five days to dry 5 mm thick mango fruit. Open-air uncontrolled solar drying has relatively low running costs, because it only requires labour. Product quality is compromised and does not meet either national or international standards (Mustayen *et al*., 2014). This is because the produce is susceptible to infestation by foreign materials, such as dust, insects and micro-organisms. In addition, there is discolouration from ultraviolet radiation and there is the chance of insufficient drying, or over-drying (Falgari *et al.*, 2008; Sharma *et al.*, 2009; Mustayen *et al*, 2014). Because of its popularity and the lack of control of the drying parameters, this study will consider open air uncontrolled solar drying as a control experiment.

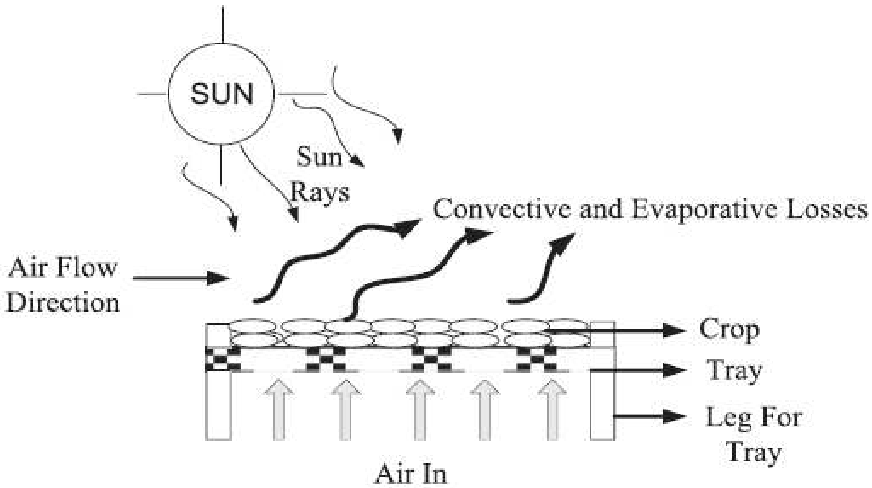

Figure 2.4 Illustration of the working principle of open-air uncontrolled solar drying (after Tiwari *et al.*, 2016)

2.6.2 Direct solar dryers

In direct type solar dryers, the produce is exposed to the sun's rays. The produce is placed in a chamber that used as a collector (Ogunkoya *et al*., 2011; Eswara and Ramkrishnarao, 2013). Akarslan (2012) indicated that it differs from open-air uncontrolled solar drying, because a transparent material covers the produce. This reduces the direct convective losses to the surrounding and increases the drying temperature (Jairaj *et al.*, 2009; Akarslan, 2012). Direct-type solar dryers typically consist of a drying chamber that is made of glass or plastic, as shown in Figure 2.6. The produce is placed in a perforated tray that allows air to flow through the fresh produce (Wakjira, 2010; Eswara and Ramkrishnarao, 2013; Toshniwal and Karale, 2013). The different types of direct solar dryers include solar cabinet dryers, greenhouse dryers, staircase dryers and glass roof dryers. These dryers are successful for drying small amounts of high moisture produce, such as mangoes, pineapples, bananas and carrots (Schiavone *et al.*, 2013). In addition, a greenhouse solar dryer is an attractive solution, for drying large quantities of produce of up to 1000 kg (Tiwari *et al.*, 2016). According to Ramana (2009) and Belessiotis and Delyannis (2010), the initial cost is relatively low, therefore more than 80% of smallholder farmers use this type of dryer. However, it requires the frequent turning, of the produce for uniform drying, because the essential component of the product is affected by radiation (Schiavone *et al.*, 2013).

This study considered modifying a greenhouse dryer for drying large quantities of produce, to promote the upscaling of production by smallholder farmers. Experiments were carried out and successful implementation was achieved in India, Thailand, Turkey, Uganda and Australia, for drying fruit, vegetables and herbs. It took four to seven days to dry 1000 kg grapes in a solar greenhouse dryer to a moisture content of about 9% (Tiwari *et al.,* 2016). Schirmer *et al.* (1996) evaluated a greenhouse solar dryer and found that it took three to five days to dry banana in temperatures ranging from 40-65˚C, and it took five to seven days when drying under open-air conditions. In addition, the essential changes required for improving a greenhouse solar dryer are simple and economical. This study intends to evaluate a modified greenhouse solar dryer under South African conditions.

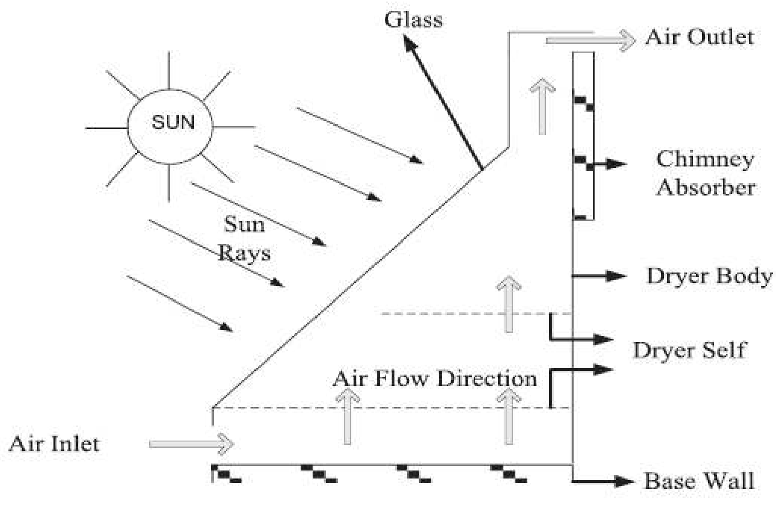

Figure 2.5 Illustration of the working principle of a direct solar dryer (after Tiwari *et al.*, 2016)

2.6.3 Indirect solar dryers

In direct dryers, the sun does not act directly on the material that is to be dried. According to Akarslan (2012), the crop is placed in trays or shelves inside an opaque drying chamber and heated by circulating air, which is warmed during its flow through a solar collector, as shown in Figure 2.6. They are used for some perishables and fruits. The vitamin content of the product is reduced considerably by the direct exposure to sunlight (Belessiotis and Delyannis, 2010). Indirect solar dryers have a higher drying rate than direct solar dryers and open sun dryers, because of the higher operating temperatures. Nahar (2009) tested the direct and the indirect solar dryers on onions, tomatoes, turmeric, coriander, okra and mints. It was found that it took 20% more time to dry, when using a direct dryer, compared to an indirect dryer. The limitation, however, is that indirect solar dryers require a large capital investment and higher maintenance costs than direct dryers (Belessiotis and Delyannis, 2010). A typical indirect solar dryer consists, of insulated ducting, a drying chamber and a solar collector. This study did not consider an indirect type solar dryer because of the increased capital costs and relatively low drying capacity associated with implementing the dryer.

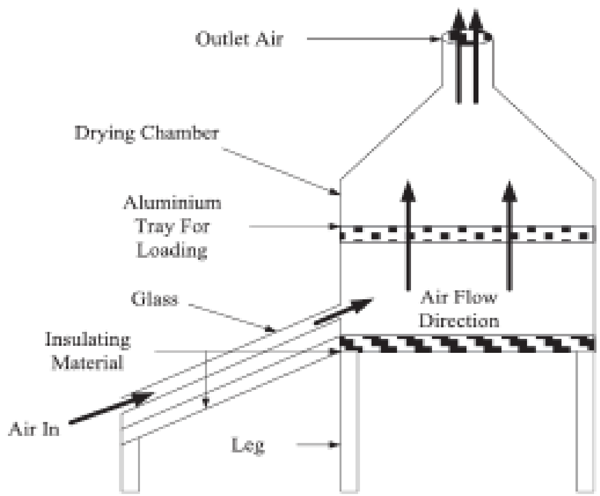

Figure 2.6 Illustration of the working principle of an indirect solar dryer (after Tiwari *et al*., 2016)

2.7 Comparison of Natural and Forced Ventilation Solar Drying systems

Naturally-ventilated solar dryers have natural air circulation. Forced ventilation utilises a fan for air circulation (Hii *et al.,* 2012). Natural convection solar dryers improve the drying time by 30-40%, compared to open sun drying (Berinyuy *et al.*, 2012). However, they have a lower drying capability than forced convection dryers do. Therefore, forced ventilation dryers are preferred for large-scale commercial operations, because the drying parameters can be varied (Sharma *et al.*, 2009). Availability of drying technology for commercial operations has led to limited research on suitable options for small-scale farmer operations. When comparing the performance parameters as shown in Table 2.2, it was found that the efficiency of the drying systems is almost the same, however, the drying time differs. Research studies indicate that a reduction of the drying time significantly retains product quality, in terms of the colour and reconstitution properties. Khazaei (2006) found that the drying time for forced convection is 55% shorter than natural convection drying, as shown in Figure 2.7. In conclusion, forced convection is a better option than natural convection drying systems. However, the capital cost increases, because of the fan, which requires a relatively high running cost. This study intends to improve air circulation in natural ventilation by using a wind ventilator, so that the dryer can be cost-effective.

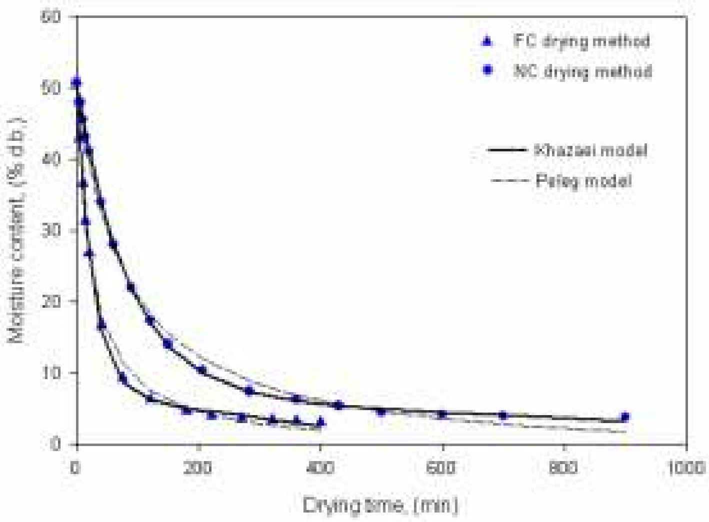

Figure 2.7 Drying time of forced convection and natural convection drying (after Khazaei, 2006)

Table 2.2 Comparison of the performance parameters of natural and forced convection solar dryers

Type of dryer	**Produce (mass, kg)**	**Relative humidity (%)**		**Temperature (℃)**		**Velocity ($m.s^{-1}$)**	**Average solar radiation ($W.m^{-2}$)**	**Drying period (hrs)**	**Efficiency (%)**	**References**
		Initial	**Final**	**Ambient**	**Average**					
Forced convection	Mushroom (160)	89.41	15	37	66.5	0.2	273-885	8	34.6	Bala *et al.*(2009)
Forced convection	Moringa leaves	80	10	25	46.5	5.37	320	24-30	25	Amedorme *et al.*, (2013)
Forced Convection	Mango	85	10	-	60, 50 and 44	0.5	-	8.8, 11.6 and 13.2	-	Mercer (2012)
Natural convection	Mango (9.80)	84	11.1	34	69	0.49	319	39	29.5	Schiavone (2011)
Natural Convection	Mango (100)	81.4	10	30	70	2	231.5	20	30	Akoy (2014)
Natural convection	Tomato, mango, fresh okra, carrot and onion (10)	93, 88, 88, 88 and 87	4, 6, 4, 5 and 6	31.4	49.9, 50.5, 52.29, 49.9 and 51.17	1.32	570	34, 36, 28, 35 and 30	-	Eke (2013)

2.8 Improving the Efficiency of Solar Dryers

As noted in the previous section, natural ventilation solar dryers are not efficient because they have a lower drying rate than forced ventilation driers. Therefore, if several innovative features are implemented , they can improve their efficiency, for example, incorporating a wind ventilator, a chimney, and the use of heat storage, as described in the sections below.

2.8.1 Wind ventilator

A wind ventilator runs on wind only and creates the necessary draught that maintains a good airflow inside the solar dryer. Chandak *et al.* (2006) found that dryers underperform when naturally ventilated and a wind ventilator enhances their ventilation rates. A wind ventilator induces ventilation, by drawing out hot air from the dryer. The wind blows on the vanes, which causes the ventilator to rotate and the rotation causes a negative pressure inside the ventilator, which extracts the air (Khan and Riffat, 2008). Bolaji and Olasusi (2011) substantiated this by evaluating the performance of a solar cabinet dryer, with a wind ventilator. The efficiency of the solar dryer with a wind ventilator was 46.7%, without a ventilator, it was 31.2%. Therefore, this study will include a wind ventilator, in order to improve air the ventilation inside the dryer.

2.8.2 Solar Chimney

A solar chimney is another way of improving the ventilation rate in naturally-ventilated dryers. This also prevents stagnation of air inside the dryer, by drawing out air from the dryer (Chen and Qu, 2014). A solar chimney consist of an internal absorber wall, which uses radiant energy to heat up the air in the chimney. It operates by increasing the buoyancy force, which is directly proportional to the difference between the mean air density within the chimney and the density of the outside air. In addition, the airflow, temperature and velocity at the outlet of the chimney also increase. Buchinger and Weiss (2002) indicated that solar chimneys have shown success in areas where the heated air is between 10-30°C. Solar chimneys are applicable to forced ventilation dryers because of the pressure difference, which then improves their performance. Consequently, the chimney with natural ventilation may not have any significance. As a result, a solar chimney will not be considered for this study.

2.8.3 Heat storage

Thermal heat storage either in the, form of sensible heat or latent heat also enhances the performance of solar dryers. The recovered solar radiation is used during low sunshine periods. Common applications of sensible heat are a gravel bed, sand, clay and concrete (Mohanraj and Chandrasekar, 2009). Heat storage maintains a consistent drying temperature and improves the drying rate. Berinyuy *et al.* (2012) evaluated the natural ventilation solar dryer, with heat a storage provided by crushed basalt rocks. The drying rate improved by 30-50%, compared to open-air uncontrolled solar drying. Thermal storage was not considered in this study because it is complicated and it requires skilled labour to operate the system. This is not an added advantage, as the prototype should be simple in design and operation.

2.9 Electrical Energy for Drying Agricultural Products

South Africa relies on Eskom for its energy production and provision. Eskom produces 95% of the energy, of which approximately 77% is produced from coal. Taylor (2009) indicated that the dependence on coal-based power stations has resulted in an annual per capita greenhouse gas emission rate of about 10 tons per year, which is 43% above the world average. This contributes significantly to climate change. Furthermore, the energy sector alone contributes about 60% to greenhouse gases (Khan *et al*., 2015). Reports show that 30% of South Africans have no energy supply (Taylor, 2009).

Furthermore, the problem of energy supply persists, because in 2008 and 2015, Eskom declared that it could no longer meet the peak national electricity demand. According to Maasdam (2008), this has led to a 350% electricity tariff increase between 2008 and 2016. As a result, electricity costs have become a burden for the food processing industry, including drying. According to Jangam *et al.* (2010) and Tchaya *et al.* (2014), the energy consumption for an industrial air-drying process ranges from 10-25% of the total industrial energy demand. Thus, running electricity dependant operations is not feasible and sustainable. Furthermore, to reduce greenhouse gas emissions, there is a need to use sustainable sources of energy to run energy-dependant operations, such as dryers. According to Sharma *et al.* (2009), many countries of the world use solar thermal systems in agriculture for the preservation of fruit. This is a practical, economical and an environmentally-friendly approach. The perception is that the modified solar drying of fruit improves the quality of the produce, compared to open-air uncontrolled solar drying and it contributes to the reduction of post-harvest losses (Wankhade *et al.*, 2012). Therefore, solar energy is one of the best alternatives for use in drying operations in South Africa.

2.10 Solar Energy Availability in South Africa

Solar energy is a source of renewable energy, which is attributed to sunlight. The energy emitted is from the sun's radiation (Duffie and Beckman, 1991; Bradford, 2006). Solar energy represents the largest source of renewable energy, compared to solid biomass, biogas, hydro, CSP, wind and geothermal sources. The sun emits energy at a rate of 3.8 x 10^{23} kW, of which 1.8 x 10^{4} kW is intercepted by the earth (Timilsina *et al.,* 2012; Tyagi *et al.,* 2012). The average solar radiation in South Africa ranges from 4.5 $kWh.m^{-2}$ – 6.5 $kWh.m^{-2}$, for an average of six to seven hours, as shown in Figure 2.8 (Fluri, 2009; van Vuuren *et al.*, 2017).

According to Saxena *et al.* (2013), this is enough radiation to be converted to heat, or electricity for thermal and electrical applications. The potential for the application of solar energy is its preservation of horticultural commodities, such as fruit through cool storage and drying. This is achieved by the conversion of solar energy to electricity for powering refrigerators, evaporative coolers and providing heat energy for drying. This study will focus on the thermal application of solar energy. This is where solar radiation is absorbed by a working fluid, which can either be water or air. Solar dryers incorporate collectors, to absorb the radiation into the working fluid/air.

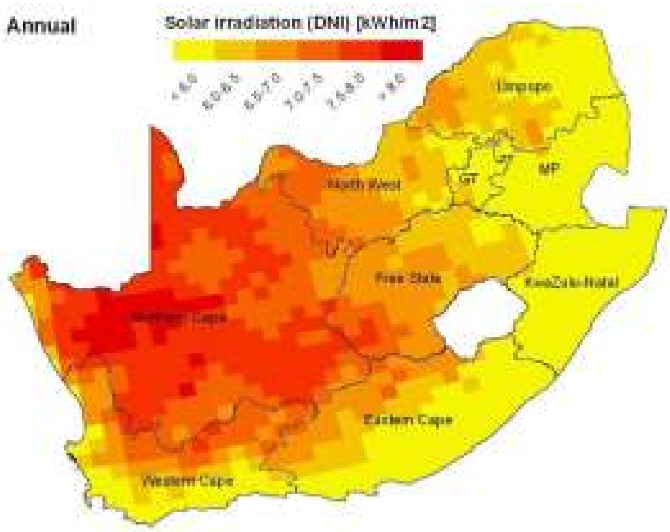

Figure 2.8 Average annual solar radiation of South African Provinces (after Fluri, 2009)

2.11 Drying Pre-treatments

The recent trend in modern food technologies is to minimize nutrient degradation during the processing and storage of fruit (Marfil *et al.*, 2008). In drying particularly, there is an interest in the enzymatic activity, which result in browning (Salunke *et al.*, 1991; Marfil *et al.*, 2008, Sagar and Suresh, 2010). This is mainly, because light-coloured fruits, such as mangoes, apples, peaches and pears darken rapidly when cut and exposed to air. Non-enzymatic reaction, such as the maillard reaction, caramelisation and the oxidation of ascorbic acid, lead to the browning of fruit (Sivasankar, 2009). In order to slow down the reactions, several studies recommend the use of pre-treatments.

Pre-treatments are techniques used to preserve the quality of fruit during drying. Pre-treatments prevents enzymatic activity, which would results in colour change, loss of flavour and nutritional quality (Barbosa-Cánovas *et al.*, 2003; Workneh *et al.*, 2014). Furthermore, several studies have shown that pre-treatments reduce the drying time (Kingsley *et al.*, 2007). Alternately, several chemical physical methods, such as sulphating, blanching, fruit juice and ascorbic acid have been used to pre-treat fruit during drying (Mohammed, 2004; Kingsley *et al.*, 2007; Tettey, 2008; Lewicki, 2009; Sagar and Suresh, 2010).

2.11.1 Sulphating

Sulphating is one of the oldest chemical pre-treatment methods. The common and commercially-used pre-treatment is potassium bisulphate (Doymaz, 2004). Sulphites are oxidants that prevent or reduce the discolouration of light-coloured fruit, by hindering enzymatic and non-enzymatic reactions. The fruit is soaked in the solution for 5-30 minutes before drying (Lewicki, 2009). Research studies have found that pre-treatment conserves the shape and shrinkage volume of produce during drying. It was found that sulphite pre-treatment increased the weight during the drying of apples and peaches. Furthermore, Tettey (2008) found that consumers preferred pre-treated dried mango due to colour, mouth feel and texture preservation. The challenge with using sulphites as a pre-treatment, is that it poses a hazard to humans, specifically those with ulcers.

2.11.2 Blanching

Blanching is the most popular physical pre-treatment method, which precedes drying. It inactivates enzymes and softens fruits. As a result, it reduces the drying time. Water or steam is used for blanching (Nisperos-Carriedo *et al.*, 1988; Lewicki, 2009). A study by Kim *et al.* (1989) showed that treated apples blanched at 40-50°C had increased firmness, compared to untreated samples. However, research studies indicate that blanching increases the water permeability of fruit (Sivasankar, 2009). Consequently, the constant drying period is elongated and the drying rate reduces (Kingsly *et al*., 2007; Sagar and Kumar, 2010). Furthermore, blanching results in the leakage of solubles from the fruit to the surrounding water, affecting the drying rate (Lewicki, 2009).

2.11.3 Fruit juice

Fruit juice, which is high in Vitamin C, is used as a pre-treatment. Sources of juice include oranges, lemons, pineapples, grapes and cranberries (Wolf *et al.*, 1990; Mohammed, 2004). The fruit juice slows down the reactions between the oxygen in the air and the chemicals in the fruit. Furthermore, it adds flavour to the fruit (Mohammed, 2004). The soaking of fruit in a fruit juice for three to five minutes is an effective pre-treatment. Lozano-de-Gonzalez *et al.* (1993) and Meza *et al.* (1995) obtained promising results with pineapple and lemon juice, demonstrating that it can be used, as an alternative to sulphates. Abano *et al*. (2013) showed that dried mango treated, with lemon juice had a relatively high overall acceptancy (15%) during a sensory analysis, compared to samples treated with ascorbic acid (20%) and salt (0%). Therefore, lemon juice pre-tretment is applied in this study, due to less effect on human health.

2.12 Quality Parameters

Quality is the sum of all desirable attributes, which make food acceptable for consumption. Quality attributes may be categorised into physical, sensory and chemical properties. Colour, flavour, fragrance, taste and nutritional properties are the attributes that make mangoes a popular crop in international markets (Sivakumar *et al.*, 2011). This section summarises the properties used to assess the quality of fruit, such as mangoes.

2.12.1 Physical properties

The physical properties of a fruit are observable attributes that consumers are initially exposed to and, therefore, they influence the consumer's decision to purchase the fruit. Fruit colour and firmness are the main physical properties used in illustration of fruit physical properties.

Colour

Colour is an important quality attribute for consumers as well as for the fruit and processing industry. According to Pathare *et al.* (2013) in practice consumer associates a pleasant flavour with an attractive colour. Colour is a measure deterioration of fruit quality during thermal processes such as drying (Pathare *et al*., 2013). The skin colour of a fruit is an important indicator of initial stage of fruit ripeness (Shewfelt and Henderson, 2003; Pathare *et al*., 2013). The most common technique of measuring colour is a colorimeter or chromameter, which uses mostly the CIELAB (Commission Internationale de I'Eclairage L*, a*, b*) colour system. It uses a three-dimensional colour coordinate system, which presumes that a human eye has three colour receptors (red, green and blue) and all other colours are a combination of the three (Pathare *et al.*, 2013). The CIELAB colour system therefore as shown in Figure 2.10, provides a good discrimination for saturated colours, as in the case of fresh and dried fruit (Perumal, 2007). The L^* refers to the lightness of the sample and ranges from black (zero) to white (100), a^* indicates the range of colours red (+) and green (-) and b^*, indicates the range of colours yellow (+) and blue(-) (Maskan, 2001). The total colour change (ΔE), chroma (C) and hue angle (H) are important indicators of the fruit colour changes that occur during drying and are calculated from using Equations 2.1-2.3(Maskan, 2001; Pathare *et al*., 2013; Akoy 2014).

$$\Delta E = \sqrt{(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2} \tag{2.1}$$

$$C = \sqrt{(a)^2 + (b)^2} \tag{2.2}$$

$$Hue\ angle = tan^{-1}\left(\frac{b}{a}\right) \tag{2.3}$$

In thermal processes, colour assess the formation of browning. Several studies show that browning is more prominent in the drying of fruit. It induces several reactions, such as pigment degradation (especially carotenoids), maillard reactions and the oxidation of ascorbic acid (Sivasankar, 2009; Korbel *et al.*, 2013). The maillard reaction and oxidation of ascorbic acid have been shown to produce a yellow-brown colour in mangoes dried at high temperatures (Chong *et al.*, 2013).

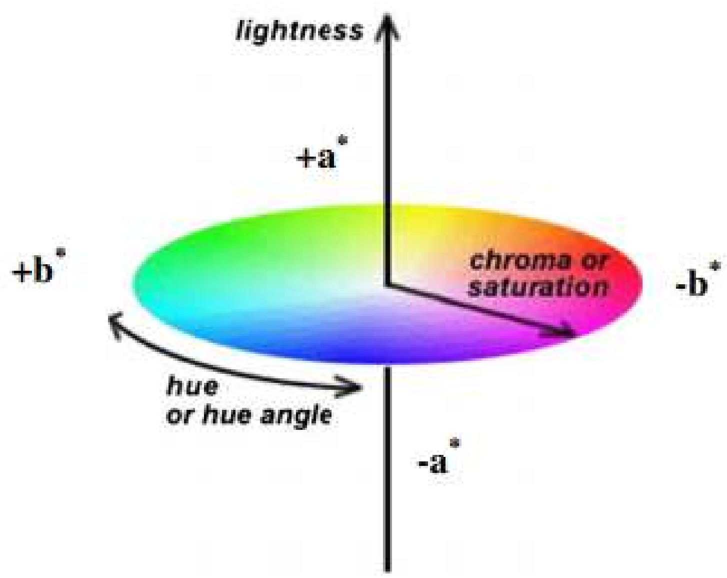

Figure 2.9 The CIELAB colour coordinate system (after Pathare et al., 2013)

Firmness

The firmness of a fresh produce is an important textural property to determine the quality. The common methods of assessing the firmness include applying of deforming forces, using puncture or compression (Abbott, 2004). These are methods which measures the force required to punch a probe into a fruit product. It is recommended to use the puncture and not the flat-plate compression for fresh fruit (Lana *et al.*, 2005).

2.12.2 Sensory properties

Sensory properties describe the eating quality of the fruit. This section highlights flavour and colour as sensory attributes used to determine quality of mango fruit.

Flavour

Flavour is a result of perception by the taste buds in the mouth (Rathore *et al.,* 2007; Saeed *et al.*, 2007). Aroma, taste and chemical mouth-feel factors contribute to flavour and these are affected by thermal operations, such as drying (Meilgaard *et al.*, 2007). Flavour is a product quality measure, perceived directly by consumers. A descriptive sensory analysis, a consumer test and preference mapping are the methods used for sensory analysis. Lawless and Heyman (2010) describe descriptive analysis as a method that provides a quantitative description of all the sensory attributes of food. The basis of a descriptive analysis is on perceptions of a group of qualified assessors.

A consumer test assesses whether consumers like a product, prefer it to another product, or find the product acceptable, based on its sensory characteristics (Tenenhaus *et al.*, 2005). Preference mapping indicates the sensory characteristics that contribute to the consumer liking a particular food product (Murray *et al.*, 2001). A Consumer test is of particular interest for this study because it is necessary to find the acceptability of the dried mango produced using the selected drying methods. Mongi *et al*. (2013) conducted a consumer test to assess the effect of drying methods on the mango fruit. The test was carried out with 78 untrained panellists who assessed the colour, mouthfeel and overall acceptability of dried mango. A 9-point hedonic scale (where one = extremely dislike and nine = extremely like) was used for scoring. Solar dried samples scored the lowest values, compared to samples dried under a solar tunnel drier.

2.12.3 Chemical properties

Total soluble solids

Total soluble solids (TSS) are an important indicator, of the maturity and quality of fruit (Guthrie *et al*, 2005). Sugars, such as fructose, sucrose, and glucose are the main component of TSS, containing a major portion of the dry matter content of fruit (Parker and Maalekuu, 2013). Fruit with low TSS has poor sensory qualities (Meilgaard *et al.*, 2007). In the processing of fruit, TSS is essential to substantiate the level of maturity before processing.

Rehydration

Pre-treatments during drying as well as drying conditions induce structural and compositional changes in food (Perumal, 2007). Rehydration behaviour is a quality measure, because it measures the damage in fruit, which is induced during drying (Lewicki, 2009). Rehydration is the ability of a fruit to reabsorb water after drying. The denaturing of proteins during drying processes, leads to a lower dehydration ratio, due to the product's inability to reabsorb water (Perumal, 2007). Oloruda *et al.* (1990) reported that tomatoes dried at lower temperature (60˚C) take in more water than those dried at 70˚C and 80˚C. Sacilik *et al.* (2006), reported that the rehydration of solar tunnel dried tomato was higher (3.15) than open-air uncontrolled dried tomato (3.10). Perumal (2007) investigated the rehydration ratio of tomato slices, of 4, 6 and 8 mm thickness dried under open-air uncontrolled solar drying and a vacuum-assisted solar dryer. The rehydration ratio was higher for the thicker (8 mm) slices. Therefore, higher drying temperatures, drying method and the thickness of dried product have an effect on the rehydration ratio.

2.13 Microbial Properties

Microbial activity accounts for the post-harvest decay of fruit by up to 15% (Workneh and Oke, 2012). The presence of micro-organisms, mainly anaerobic bacteria and fungi significantly reduces the quality. Fresh fruit is a significant source of plant and human pathogens (Gultie and Sahile, 2013; Tasirin *et al*., 2014). Bacteria, yeast and moulds are micro-organisms, which thrive in fresh fruit. Therefore, drying has been demonstrated to reduce the microbial activity in fruit. Hence, dried fruit should carry acceptable levels of micro-organisms (Ntuli *et al*., 2017).

2.14 Modelling of drying process

The mathematical modelling of the drying process of agricultural produce allows for the prediction of their behaviour during the drying process. Thin-layer drying models, such as the Exponential, Henderson and Pabis, Two-term, Logarithmic, Page, Thompson and Wang and Sing models, as describe in Table 2.5 (Belessiotis and Delyannis, 2010). In these models, the experimental Moisture Ratio (MR) is termed by the Ficks diffusion Equation 2.4:

$$MR = \frac{M_t - M_e}{M_i - M_e} = e^{-kt} \qquad (2.4)$$

Where MR (dimensionless) is the moisture ratio, M_t (%) is the dry basis moisture content at any time, M_i and M_e (%) are the initial and equilibrium dry base moisture content, k (kg.min^1) is the drying rate constant per minute and t (min) is the drying time. To select a model that best describes the drying process, the correlation coefficient (R^2) is the primary criteria used. The reduced chi-square (X^2) and the root mean square (RMSE) are used to determine the quality of the fit. Deshmukh *et al*. (2014) tested a mixed mode solar cabinet dryer for drying freshly-harvested ginger from a moisture content of 61.50%, to a moisture content of 12.19%.

Drying curves showed that drying occurred during the falling rate period and no constant period was observed. The data was fit in five thin layer-drying models and the Page model was more suitable in describing the drying kinetics of ginger in a solar dryer, under natural ventilation. Darvishi *et al.* (2013) tested a laboratory scale microwave-convective dryer for green peppers, at microwave power of 180, 360, 540 and 720W. The moisture reduction was from 2.894 to 0.1 kg^{-1} dry matter. The drying data fit to the drying the models and the Midilli Model was a best fit to the experimental data. It had the highest R^2 of 0.927, and the lowest RMSE of 0.2065 and X^2 of 0.0555. Akpinar *et al.* (2004) tested parsley leaves in a forced convention solar dryer, with an airflow rate of 1 m.s^{-1} and temperatures of 56, 67, 85 and 93°C and open-air uncontrolled solar drying. The drying process took place in the falling rate period. The drying data was fit to ten drying models. In comparing the coefficient (R), reduced chi-square (X^2) and the root mean square error (RMSE). The Page Model was the best fit for forced convection dryer and the Verma Model was best fit for open-air uncontrolled solar drying. This study intends to fit in four drying models on the drying data to illustrate the drying process of mango fruit. As illustrated in the above studies models have been successful in describing optimal conditions for operating dryers, as well as the drying process.

Table 2.3 Selected thin layer-drying models

Model name	**Model Equation**	**References**
Lewis	$MR = \exp(-kt)$	Deshmukh *et al.*, (2014)
Page	$MR = \exp(-kt^n$	Wang *et al.,* (2007)
Henderson and Pabis	$MR = aexp(-kt)$	Motevali *et al.,* (2011)
Midili	$MR = aexp(-kt^n) + bt$	Midilli *et al.*, (2002)

MR (dimensionless) is the predicted moisture ratio, k (hr^{-1}) is the drying constant, t (hr) is the drying time and a, b, n are drying model coefficients.

2.15 Discussions and Conclusions

The South African population is increasing rapidly. Estimates by STATS SA indicate that the population will be at 82 million people by 2035. Agriculture is the basis of food production and therefore the activities need to meet the food demands of the rapidly growing population. Smallholder farmers are able to produce more than their immediate consumption needs. However, they experience high post-harvest losses, which can be up to 50% (Mashau *et al.* 2012; Maremera, 2014). The population demands can be met if these losses are significantly reduced. Consequently, much research has focused on conventional drying technologies, such as freeze drying, microwave drying and vacuum drying to improve the shelf-life of fresh produce and to reduce post-harvest losses.

However, the available technology is not affordable for smallholder farmers, because of the high capital and running costs. The energy scarcity and high electricity tariffs experienced in South Africa also limit the resource-poor farmers from attaining such technology. The use of solar energy as an alternative energy source to electricity could be a solution, because it offers renewable and sustainable energy. Therefore, this study proposes to develop a modified ventilation solar dryer. Research studies indicate that drying prevents the effects of microbial activities, physiological deterioration and the further handling of produce, which cause mechanical injuries.

South Africa receives enough solar radiation that can be used for energy-intensive processes, such as drying (Rajkumar, 2007; Fluri, 2009; van Vuuren, 2017). Smallholder farmers commonly use open-air uncontrolled solar dryers globally. However, research studies show that they alter the nutritional structure of fruit, thus producing low quality produce that is not acceptable for human consumption, according to national standards (Rajkumar, 2007; Ntuli *et al.*, 2017). Freeze-drying, microwave and vacuum dryers are more efficient than open-air uncontrolled solar dryers. However, they are not affordable for the farmers, because they either require a high level of expertise for operation or a high capital and running cost. Modified solar drying is an improvement to open-air uncontrolled solar drying and consists of a collector and a drying chamber. Using a greenhouse is a feasible solution, as it allows for drying produce up to 1000 kg.

Literature studies have found that naturally-ventilated solar dryers have a lower drying rate than forced ventilation dryers. Supposedly, this contributes to the quality of produce being compromised (Akoy, 2014). Therefore, innovative options, such as the use of thermal storage, a solar chimney and a wind ventilator were considered, to improve the drying time and rate. A wind ventilator is an option that could be beneficial for a naturally-ventilated system. The study has identified a research gap in solar drying, which will improve the system's performance and be beneficial for smallholder farmers. Furthermore, studies on comparison of the popular drying methods used in South Africa still lag behind, specifically in mango drying. The drying process will be analysed, by using models to establish the optimal drying conditions. Therefore, this study will also fill in a research gap in illustrating the drying characteristics and the quality characteristics of dried mango.

The literature review showed that developing a solar dryer with improved ventilation could be a solution that would benefit mostly smallholder farmers. These are usually resource-poor farmers who are dependent on agriculture for the improvement of their livelihoods.

However, they are not necessarily able to meet their livelihood needs because they are not able to make a profit from all fresh produce sales. Preservation by drying will provide a simple technology. It may also provide new business ventures and opportunities to filter through the local fruit markets.

2.16 References

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3. THE EFFECTS OF HOT-AIR DRYING METHODS ON THE DRYING OF MANGO CHARACTERISTICS AND MODELLING

Abstract

Mango (*Mangiferia indica L.*) is an important fruit in South Africa. It is harvested once-off during the summer months. Due to a lack of appropriate, effective preservation technologies, most resource-poor smallholder farmers experience relatively high post-harvest losses of their produce. Drying is a heat and mass transfer process wherein there is a transfer of water, by diffusion, from inside the food material to the air-food interface and from the air-food interface to the outside air, simultaneously; by convection. Improved solar drying generates relatively high temperatures, has a low relative humidity, a short drying period and is relatively inexpensive. In addition, research shows that an enhanced solar dryer, such as a modified ventilation solar dryer, shortens the drying time by 65% when compared to open-air uncontrolled solar drying. This study investigated three hot air drying methods to evaluate the drying characteristics of mango. These include oven drying (OVD), open-air uncontrolled solar drying (OAD) and modified ventilation solar drying (MVD). Mango samples of 3 mm, 6 mm and 9 mm slice thickness, with and without lemon juice pre-treatment were dried from a moisture content of 79±1.6%wb to 10±0.9%wb. The study findings showed that the drying time and drying rate were significantly ($P<0.05$) affected by mango thickness. In all drying methods thinner slices dried for a shorter period, mango slices of 3 mm thickness took 3 hours in OVD, 4 hours in MVD and 11hours in OAD, compared to the 6 mm thickness which took 4.5, 9 and 14 hours for OVD, MVD and OAD, respectively. The 9 mm thickness mango took 9, 14 and 20 hours for OVD, MVD and OAD, respectively and had the longer drying times. Pre-treatment did not have an effect on the drying time and drying rates. Most of the drying took place at the falling rate period and a constant drying rate was observed for 9 mm slices dried in OVD. Four mathematical models were tested to estimate the drying coefficients by the non-linear regression method, for both drying methods to find the best fit of the moisture ratio models. The Midilli *et al.* model was the best model for predicting the moisture ratio of mango slices dried using OAD, MVD and OAD, based on statistical parameters R^2, $x^2$and RMSE.

Keywords: *Drying rate, drying time, thickness, pre-treatment, drying model, moisture*

3.1 Introduction

Drying is a post-harvest process that preserves fruit. In South Africa, the price of dried mango remains relatively high, even during the harvesting season. Hence, drying is an alternative preservation technology that could assist mango farmers in making profitably sound businesses. Open-air uncontrolled solar drying is a popular thin-layer drying method used for the preservation of fruit. It is a direct method of drying, whereby the commodities are exposed to ambient air conditions and direct sunlight. The material absorbs the solar radiation (Elkhadraoui *et al*., 2015). Several research studies have found this method to have shortfalls, which compromises the quality of the dried product. The shortfalls include longer drying periods, fungal growth and insect infestation (Misha *et al.*, 2013; Fadhel *et al*., 2014). Kumar *et al.* (2013) found that insects and rodents destroyed mushrooms that were dried under open-air uncontrolled solar drying and that the drying time and rate was also slow.

Studies have found that a greenhouse/ tunnel solar dryer is satisfactory and competitive with open-air uncontrolled solar drying (Farhat *et al.*, 2004; Fadhel *et al*., 2014). However, they have poor ventilation. As a result, naturally-ventilated cabinet solar dryers have are a popular solar drying method (Pangavhane *et al.*, 2002; Fadhel *et al*., 2014). Modified ventilation employed on a greenhouse solar dryer also uses the direct drying method, however, it is not commonly applied (Elkhadraoui *et al.*, 2015). Improved solar drying generates relatively high temperatures, has a low relative humidity, a short drying period and is relatively inexpensive. In addition, research shows that an enhanced solar dryer, such as a modified ventilation solar dryer, shortens the drying time by 65% when compared to open-air uncontrolled solar drying (source).

The challenge with use of naturally-ventilated cabinet solar dryers is their limited capacity and the relatively high cost of construction (Fadhel *et al*., 2014). Kumar *et al.* (2013) showed that a naturally-ventilated solar greenhouse dryer could take up to seven hours to dry mushroom at ambient temperature variations between 29°C and 32°C. The conclusions made by Fadhel *et al*. (2014) also indicate that a modified ventilation solar greenhouse dryer reduces the drying time. Convective oven drying is a controlled and faster way of drying fruit (Ali *et al.*, 2016). However, the cost of removing water during drying is relatively higher (Kumar *et al*., 2013). In addition, considering high electricity tariffs in South Africa, this method can increase the operation costs. Research focus is on identifying suitable drying technologies, which can scale-up production capacities, and on identifying optimal operation parameters (Tripathy and Kumar, 2017). These include, modified solar dryers, such as modified ventilation solar dryers using a greenhouse.Drying characteristics are generally evaluated experimentally by measuring the weight of drying material as a function of time (Fudholi *et al.*, 2011). Drying curves are used to represent the drying characteristics using three different plots of moisture content versus time, drying rate versus time and drying rate versus moisture content (Fudholi *et al.*, 2011). Several research studies have shown that the time and drying rate are affected when the material is subjected to known temperature and relative humidity air conditions.

However, there is limited research to determine the effect of product thickness and pre-treatment on drying kinetics, especially for mangoes. Mathematical modelling is important for the management of operating parameters. Empirical models depict the drying process by showing the model that best fits the experimental moisture ratio data (Perumal, 2007). There has also been extensive research on thin-layer drying characteristics and modelling, for various fruit, including several drying methods. However, information is lacking with regard to a comparison the three methods considered in this study. Therefore the objectives of this study were:

(i) to comparatively investigate the drying kinetics of mango slices treated with lemon juice as well as untreated slices dried, using convective oven drying, uncontrolled open-air solar drying and a modified ventilation solar drying,

(ii) to comparatively investigate drying models and determine a drying model which best fits the drying data, and

(iii) to comparatively investigate the effective moisture diffusivity of the three drying methods.

3.2 Materials and Methods

3.2.1 Study area

The comparative performance evaluation of open-Air uncontrolled solar Drying (OAD), Modified Ventilation solar Drying (MVD) and convective Oven Drying (OVD) was carried out at the Ukulinga Research Farm, located at 30°24' S" and 29°24' E and at an altitude of 721 m (above sea level) in Pietermaritzburg, in the KwaZulu-Natal Province of South Africa. The long-term average minimum and maximum temperatures range between 6.0-16.4℃ and 20.6-27.4℃ (Thipe, 2014). The average wind speed of Pietermaritzburg reported for the past two decades was 0.8 m. s^{-1}, with a maximum of 9.7 m. s^{-1}. The prevailing wind direction is east –southeast (Schulze and Maharaj, 2007). The daily average relative humidity is between 61.1-75.3% and solar radiation 15.1-27.8 $MJ.m^{-2}.day^{-1}$ (Schulze and Maharaj, 2007). This site was selected because the ambient air conditions are within the acceptable range for conducting the OAD and MVD experiments. An ambient air temperature of about 30℃ is acceptable for open air solar drying (Akarslan, 2012; Paul and Singh, 2013). MVD can increase temperature by about 25℃ above the ambient temperature, therefore the lower and higher temperatures will be able to meet the required optimum temperatures of 55-65℃ for the drying of mango fruit (Goyal *et al.*, 2006). In addition, the relative humidity values of the area are within the ranges that have been tested by Kaya *et al.* (2007). The solar radiation received in the area is sufficient for use in drying applications (Saxena *et al.*,2013). In addition, the site selected had research resources and equipment as well as skilled researchers and a workshop with skilled technicians.

3.2.2 Sample preparation and treatments

A batch (150 kg) of process grade Tommy Atkin mangoes was acquired from ZZ2 (Limpopo, South Africa). The sample was prepared immediately after delivery, at room temperature. Mangoes were sorted according to skin colour. The mango samples were washed and the skin peeled, using a hand peeler. The whole fruit was cut lengthwise, along the fibre into 3 mm, 6 mm, 9 mm slices using a knife, and the seed was removed. Lemon juice (100%) was used as pre-treatment to dip the slices for 5 minutes at room temperature. Dried samples were kept in labelled zip lock bags after drying (Victoria packaging, Pietermaritzburg, South Africa).

3.2.3 Description of drying methods

Modified ventilation solar drying

A 48 m^2 floor area greenhouse structure with a width of 8 m, length of 6 m and a height of 3.25 m was used for the MVD experiment. The structure was oriented in an east-west direction. The frame was of galvanised steel, with the parabolic roof structure covered with 200 µm ultra-violet polyethylene plastic film. The flooring was compacted soil, covered by a black mat. The greenhouse was modified by including a natural ventilation system through three louvers (0.5 x 0.5 m), located in the middle of the east side of the dryer. Air exhaustion from inside the dryer was by means of two wind ventilators on the top of the roof, as shown in Figure 3.1. The mango slices were dried in a thin-layer on two drying trays (3 m length x 1.45 m width) made of galvanised steel, with a perforated tray base and galvanised steel legs.

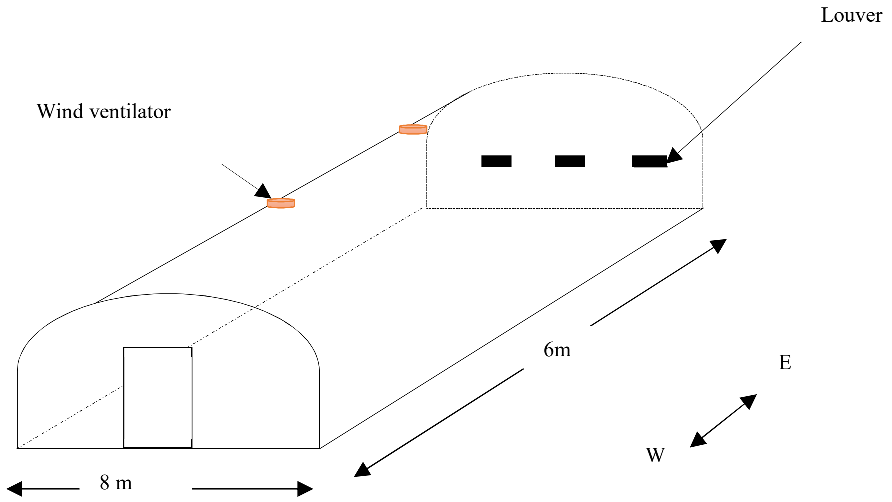


Figure 3.1 Schematic diagram of MVD dryer

Open-air uncontrolled solar drying

The thin-layer drying of mango slices was under uncontrolled open sun conditions. The experiment was carried out simultaneously with MVD experiments. Samples of mango slices were on steel trays of 6 m^2 surface area.

Convective oven drying

Oven air-drying was carried out at 70℃ (de Medeiros *et al.*, 2016) using a forced air oven dryer (Prolab, PRIS, RSA). The dryer was run for 2 hours before placing samples inside for it to obtain stable conditions.

3.2.4 Experimental design

The experiment was designed, based on the Randomized Complete Block Design (RCBD), with three blocks, namely, OVD, MVD and OAD. Evaluations were carried out for mango slice thickness (3 mm, 6 mm and 9 mm) as well as control and a lemon juice pre-treatment. Each experiment was replicated three times to attain accuracy as seen in Appendix 3.1.

3.2.5 Data collection

Drying air conditions

Ambient air conditions (temperature, relative humidity and solar radiation) were obtained from a weather station that is based at Ukulinga Research Farm. Five data loggers recorded air conditions inside the dryer (Hobo U12-013). The dots in Figure 3.2 represent the position of the data loggers. Two sensors were directly below each wind ventilator and one sensor was at the air inlet (louver opening). Two sensors were placed on top of each drying tray.

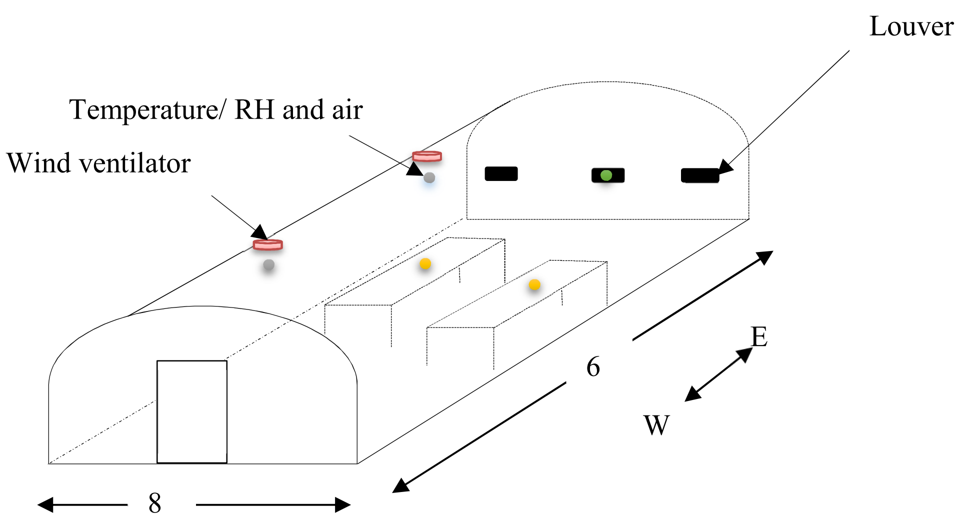


Figure 3.2 Illustration of the positions of data loggers inside MVD

Moisture content

The weight loss during drying was used to measure different moisture contents, namely; (i) the initial moisture content (M_i), (ii) the instantaneous moisture content (M_x) and (iii) the equilibrium moisture content (M_e). The weight loss was monitored at fixed intervals of 30 minutes for OVD and one hour for OAD and MVD by removing samples from the dryer and measuring the weight, using a digital weighing balance (Avery Berkel, Model TB151-C4ZA10AAR, UK) with an accuracy of ±0.1 g. The samples were dried for 48 hours at 70℃, as in the AOAC (2000) method in a convective oven dryer to determine the initial moisture content (Workneh and Oke, 2012; Mercer, 2012). In order to, determine the equilibrium moisture content the sample was dried for 48 hours at 105℃ as in AOAC (2000) method in a convective oven dryer to estimate the equilibrium moisture content (Workneh and Oke, 2012; Mercer, 2012).

3.2.6 Temperature, relative humidity and solar radiation data analysis

A statistical analysis of the temperature and relative humidity was carried out using the Analysis of Variance (ANOVA) one way and a general ANOVA analysis in the VSNI-Genstat® data analysis tool (version 18.20.18409).

3.2.7 Drying characteristics data analysis

Moisture content drying curves

The instantaneous and initial moisture content of dried produced is determined, by using Equation 3.1 and 3.2 respectively. Drying curves were generated, by using Microsoft Office Excel (2010).

$$M_{cx} = \frac{w_x - w_f}{w_x} \times 100 \tag{3.1}$$

The instantaneous moisture content, M_{cx} (% wb), is determined by the weight measured at a specific time during drying w_x (g) and w_f (g) is the final weight measured during drying.

$$M_i = \frac{w_i - w_f}{w_f} \times 100 \tag{3.2}$$

M_i (% wb) is the dry basis moisture content, w_I (g) is the initial weight and w_f (g) is the final weight of product.

Drying rate

The drying rate was estimated, by using Equation 3.3. Drying rate curves were generated on Microsoft Office Excel (2010).

$$DR = \frac{M_{t+dt} - M_t}{d_t} \tag{3.3}$$

DR ($kg.hr^{-1}$) is the drying rate, M_{t+dt} (% wb) is the moisture content at the time t+dt, M_t (%wb) is the moisture content at the time t and t (hr) is the drying time (Akhijani *et al.*,2016).

Mathematical modelling

The sample's experimental moisture ratio was determined by Equation 3.4. Non-linear regression was carried out to determine the goodness of fit of the selected models, shown in Table 3.1 to the experimental moisture ratio. The Microsoft Office Excel (2010) solver tool was used to estimate the drying coefficients and the coefficient of determination (R^2) for the different drying models. The Chi-square (x^2) and Root Mean Square (RMSE) were determined, by using Equation 3.4 and 3.5 respectively. The higher the R^2 values and the lower the x^2 and RMSE, the better the goodness of fit.

$$MR = \frac{M_{cx} - M_e}{M_i - M_e} \tag{3.4}$$

MR (dimensionless) is the moisture ratio, M_{cx} (%wb) is the instantaneous moisture content, M_e (%wb) is the equilibrium moisture content and M_i (%wb) is the initial moisture content (Perumal , 2007).

$$x^2 = \frac{\sum_{i=1}^{N}(MR_{pre,i} - MR_{exp,i})^2}{N - z} \tag{3.5}$$

x^2 (dimensionless) is chi-square, $MR_{pre,i}$ (dimensionless) is the predicted moisture ratio and $MR_{exp,i}$ (dimensionless) is the experimental moisture ratio, N is the number of observations and z is the number of constants (Akhijani *et al.*, 2016).

$$\mathrm{RMSE} = \left(\frac{\sum_{i=1}^{N}(\mathrm{MR}_{\mathrm{pre,i}} - \mathrm{MR}_{\mathrm{exp,i}})^2}{N}\right)^{\frac{1}{2}} \tag{3.6}$$

Where, RMSE (dimensionless) is the root mean square, $MR_{exp,i}$ (dimensionless) is the experimental moisture ratio, N is the number of observations.

Table 3.1 Selected drying models

Model name	Model equation	References
Lewis	$MR = \exp(-kt)$	Deshmukh *et al.* (2014)
Page	$MR = \exp(-kt^n)$	Wang *et al.* (2007)
Henderson and Pabis	$MR = aexp(-kt)$	Motevali *et al.*(2011)
Midilli *et al.*	$MR = aexp(-kt^n) + bt$	Midilli *et al.*(2002); Hayaloglu *et al.*(2007)

MR (dimensionless) is the predicted moisture ratio, k (hr^{-1}) is the drying constant, t (hr) is the drying time and a, b, n are drying model coefficients.

3.2.8 Effective moisture diffusivity

Fick's law of diffusion is widely used to describe drying in the falling rate, where diffusion is the dominant drying mechanism of fruit (Akpinar, 2006; Perumal, 2007; Duc *et al.,* 2011; Hashim *et al.,* 2014). Fick"s equation solution was developed, by Crank (1975) and assumes that, in the drying period there is, uniform initial moisture distribution, moisture migration is by diffusion, negligible external resistance, negligible shrinkage, constant diffusivity and temperature.

$$MR = \frac{M_{cx} - M_e}{M_i - M_e} = \frac{8}{\pi^2}\exp\left(\frac{-\pi^2 D_{eff} t}{4L^2}\right) \tag{3.7}$$

The moisture ratio, MR (dimensionless), M_{cx} (%wb) is the instantaneous moisture content, M_e (%wb) is the equilibrium moisture content, M_i (%wb) is the initial moisture content, D_{eff} ($m^2.s^{-1}$) is the moisture diffusivity, t (s) is the drying time and L(m) is the half slab thickness, as shown in Equation 3.7 Olanipekun *et al.* (2015).

The slope of the lnMR versus time graph was used to estimate to determine the effective moisture diffusivity.

$$K = \frac{\pi^2 D_{eff} t}{4L^2} \tag{3.8}$$

The slope, K (dimensionless) was obtained from lnMR versus time graph (Appendix 3.2), as shown in Equation 3.8 (Doymaz, 2007; Olanipekun *et al.* 2015).

3.3 Results and Discussions

3.3.1 Ambient air conditions during drying

Ambient air conditions include temperature, relative humidity and solar radiation. Measurements were taken on an hourly basis between 8.00 am and 16.00 pm from 18-20 January, as shown in Figure 3.3. The ambient temperature varied from a minimum of 15.55˚C to a maximum of 36.77 ˚C during the drying period. The mean temperature on first day was 22.35˚C, 30˚C on second day and 33.16˚C on the third day. Observations of the highest temperatures were between 14.00 pm-15.00 pm on the first day. On the second day, however, the highest temperature was at 12.00 pm and the temperature started going down at 13.00 pm. On the third day, the highest temperature was between 13.00 pm-14.00 pm. The mean temperature during the drying period was 28.50˚C. Figure 3.3 shows that the mean temperatures during the drying period differ significantly (P<0.001). The mean temperature on first day was significantly lower (P<0.001) than for second day, by 7.65˚C. The mean temperature of the second day was not significantly lower than for the third day (P>0.05), with a difference of 3.16˚C.

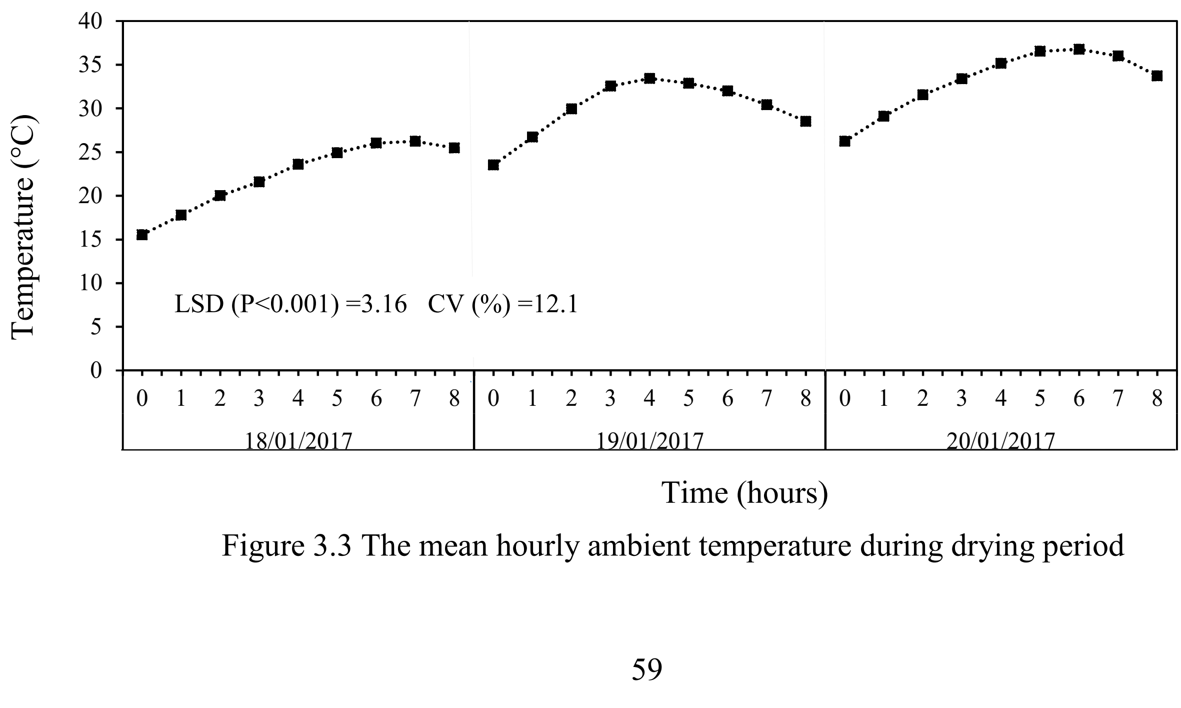


Figure 3.3 The mean hourly ambient temperature during drying period

The relative humidity varied significantly during the drying period ($P \leq 0.05$), as shown in Figure 3.4. The mean minimum relative humidity observed was 22.96% and a maximum of 79.06%. The mean relative humidity observed during the drying period was 44.3%. On the first day it was significantly lower ($P<0.05$) than for the second day, by 10.1%. However, the mean relative humidity observed on second day was not significantly lower ($P>0.05$) than the third day. Observations indicated that relative humidity is at its lowest where the temperature is higher.

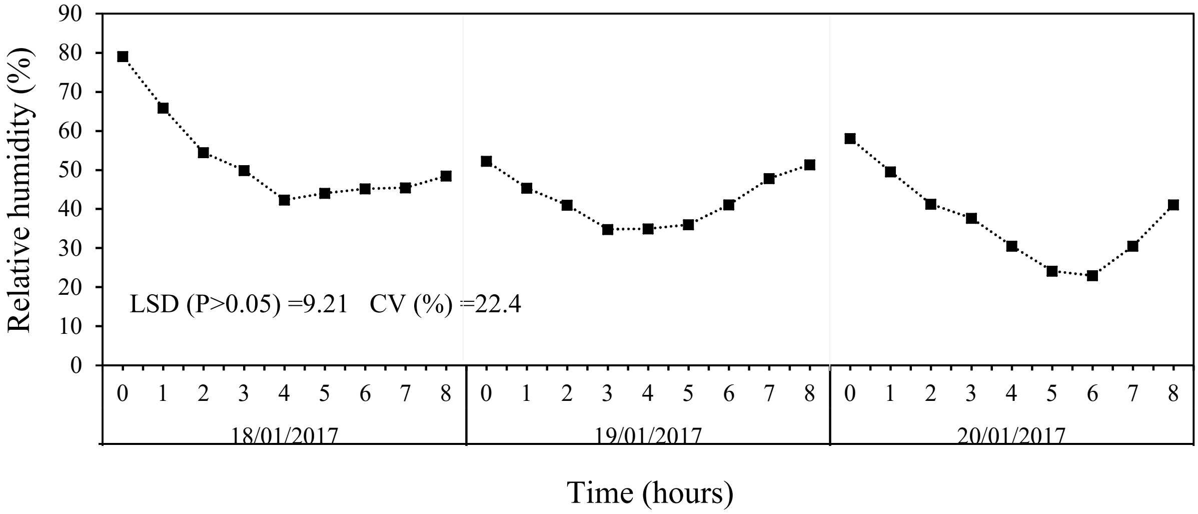


Figure 3.4 The mean hourly ambient relative humidity during the drying period

An average of 769 $W.m^{-2}$ was observed during the 8-hour daily drying period, as shown in Figure 3.5. The solar radiation was at its highest of 1016.203 $W.m^{-2}$ on the first day, at around 12.00 pm-13.00 pm and lowest on the third day, at 16.00 pm. During the three-day drying period, the highest temperature and solar radiation were observed between 12.00 pm-14.00 pm. Studies by Perumal (2007) made a similar observation of ambient air temperature increase with solar radiation. The observed ambient air meteorological data clearly indicate that the solar drying of mango can be carried out during harvest season (Perumal, 2007; Akarslan, 2012; Paul and Singh, 2013).

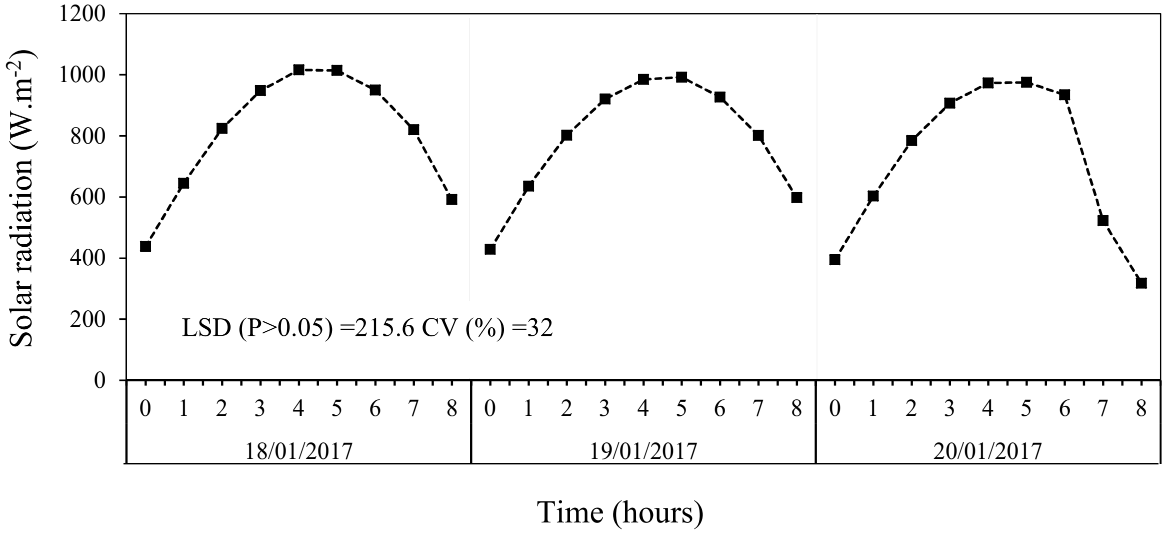
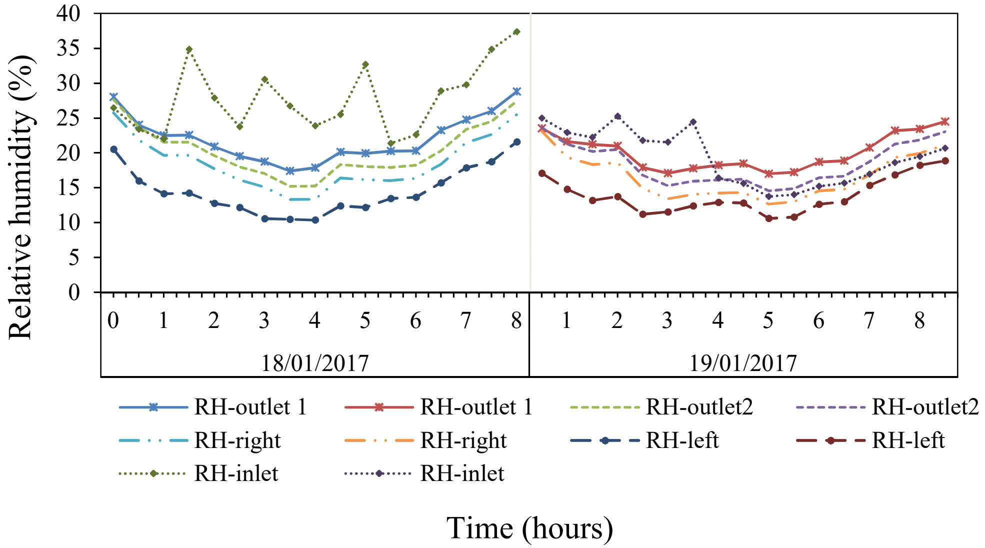


Figure 3.5 The mean hourly solar radiation during the drying period

3.3.2 Climatic conditions inside MVD

During the two days in the MVD the mean temperature inside the dryer was 49.33˚C and the relative humidity was 23.58%. It was observed that there was a highly significant ($P<0.001$) difference in the temperature at the various points of measurement inside the dryer. The highest mean temperature of 64.26˚C was observed at the product level, as shown in Figure 3.6 (T-right and T-left) on the second day with the lowest of temperature 31.28˚C at the air inlet on the first day. The mean temperature at the outlet had reduced significantly ($P<0.05$), compared to the air inlet temperature during the drying period. Inside the dryer, the air temperature increase was significantly higher ($p<0.001$), and a 7.24˚C increase from the air inlet temperature was observed, with the highest value of 64.24˚C observed inside the dryer. The temperature on product level (drying tables) did not differ significantly ($P>0.05$). The temperature was 1.14˚C higher on the left side. The mean relative humidity had increased significantly ($P\leq0.001$) at the air outlet, compared to the air inlet. It increased by 4.35% inside the dryer during the drying period. In addition, the relative humidity at products placed on left and right of the greenhouse was significantly different ($P<0.001$), with the left being lower than the right, by 3.39%. Tiwari *et al.*, (2006) investigated a naturally-ventilated modified ventilation solar dryer, using a greenhouse solar dryer for drying prawns. The ambient temperature for two days varied between 33-39˚C. The dryer increased the product temperature to between 41 and 51˚C. This study also showed that there is a substantial increase in the ambient temperature and a reduction of the relative humidity, creating favourable conditions for drying, due to an increase of the evaporative capacity of air. Ayyappan and Mayilsamy (2010) investigated a solar greenhouse dryer for copra. The highest solar radiation was at 800 $W.m^{-2}$, RH and temperature of ambient air conditions were 60% and 30˚C respectively. Inside the dryer, and the RH reduced to 30% and the temperature increased to 60˚C. Similar observations of effect of a greenhouse were observed in the study, where the RH reduction and temperature increase were a double of the ambient values. Kaewkiew *et al*. (2012) observed a significant difference between ambient air conditions and a modified forced-ventilated solar dryer, using a greenhouse, where it was also indicated that the relative humidity and temperature vary in the air inlet and outlet, with the air leaving the dryer at a lower relative humidity than the ambient air and air at the inlet. Similar observations were made in this study, indicating that the air from the outlet of the dryer can be recirculated for drying. In 2015, Elkhadrauoi *et al.* (2015) modified a greenhouse for drying chilli. It was found that the temperature inside the dryer increased from a range of 21.25-35.71˚C to 27.87-54.68˚C, using a mixed mode dryer. The relative humidity was lowered to 17.62%. The dryer tested in this experiment showed relatively lower relative humidity values, reaching about 10% at product level. The findings indicate that a naturally-ventilated MVD is an option, as it has the potential for performing better than a mixed mode solar dryer.



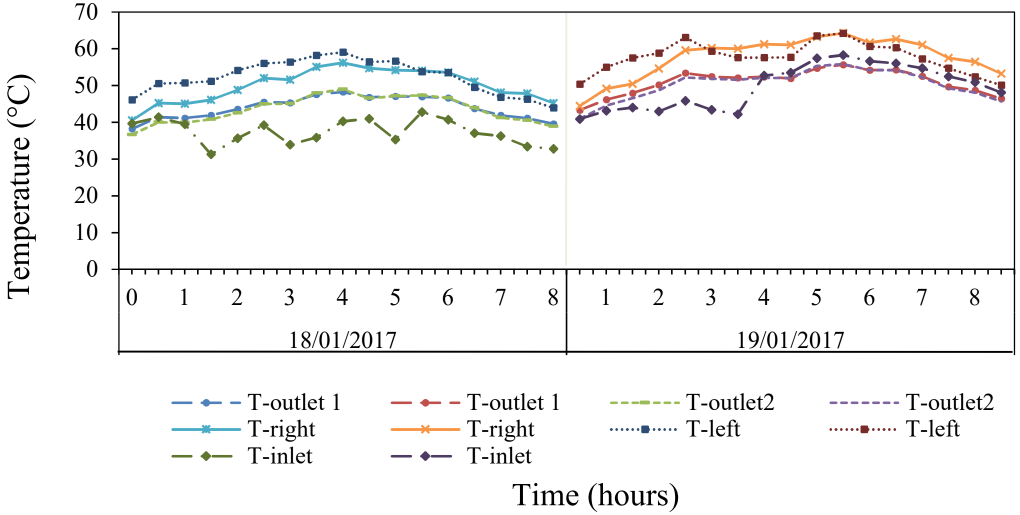


Figure 3.6 Temperature and relative humidity variations inside MVD

3.3.3 The effect of pre-drying treatments and slice thickness on drying time

The drying of mango fruit was carried out from a fresh mango moisture content of 79±1.6% wb to a moisture content of 10±0.86% wb. Observations in OVD indicate that the drying time did not vary for control and lemon juice pre-treated mango slices of the same thickness, as shown in Figure 3.7. There was no significant (P>0.05) variation in the moisture content lemon juice treated and control samples. However, a significant (P<0.001) variation of drying time was observed, as the mango thickness changed. Thicker mango slices (9 mm) were observed to have a significantly (P<0.05) longer drying time than thinner slices (3 mm), the drying taking three times longer for the thinner slices.

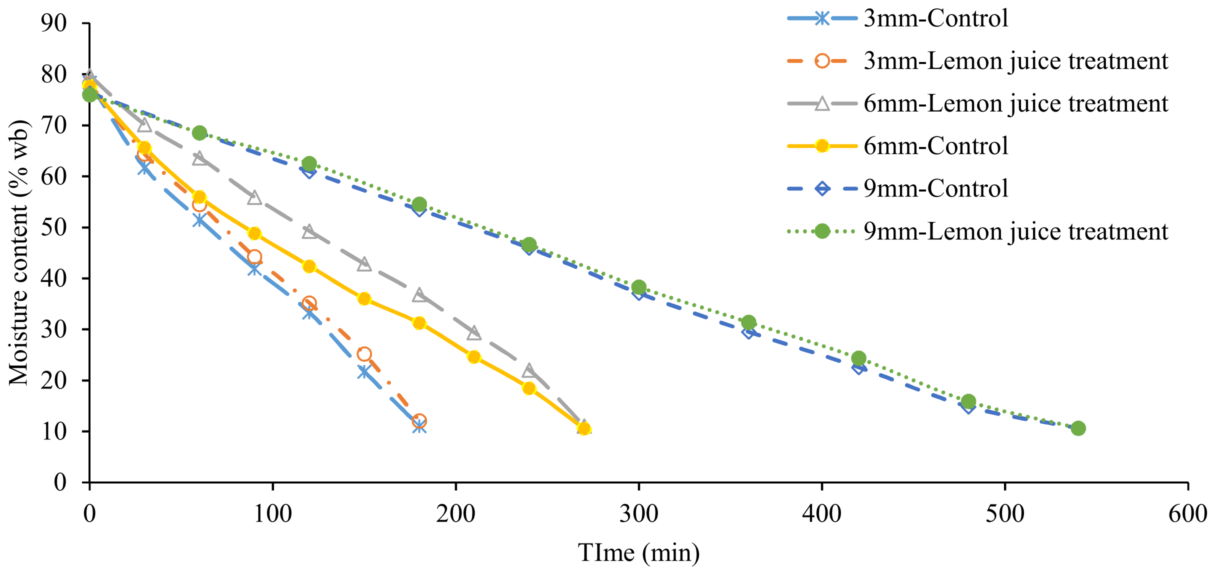


Figure 3.7 Moisture content variation of OVD during drying period

In MVD, similar observations were made indicating no significance (P>0.05) in drying time and moisture loss of treated and untreated mango slices of similar thickness, as shown in Figure 3.8. The drying time was significantly (P<0.001) longer for thicker mango slices (9 mm), compared to 6 mm and 3 mm slices. Compared to OVD, it took a significantly (P<0.001) longer to dry produce in MVD, 3 mm mango slices took up to an hour longer. Similarly, 6mm slices dried in MVD took 270 minutes longer to dry and 9 mm slices took 360 minutes longer to dry. Furthermore, the 6mm mango slices were dried for just over one day and 9 mm mango slices were dried in two days.

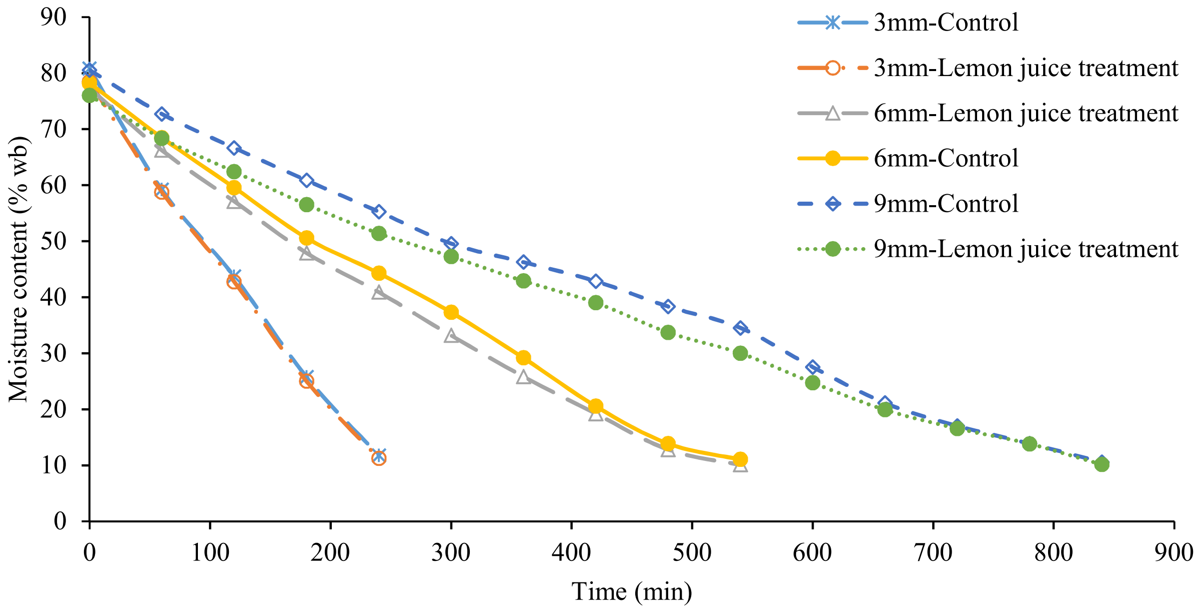


Figure 3.8 Moisture content variation of MVD during drying period

Investigations into OAD indicated similar results, where lemon juice treated and control mango slices having no significant (P>0.05) difference in drying time for each mango slice. Observations also indicated a significant (P<0.05) difference in drying time between lemon juice treated and control mango slices of 3 mm, 6 mm and 9 mm, as in Figure 3.9. It was observed that 9 mm mango slices dried in three days (1200 minutes), 3 mm and 6 mm mango slices took two days, and 6 mm slices took about 120 minutes longer to dry. Overall observations indicate that mango slices dried in OAD took significantly (P<0.001) longer to complete drying, compared to OVD and MVD. Thickness significantly affects the drying time and a pre- treatment of lemon juice does not affect the drying time. Abano and Sam-Amoah (2011) also found that pre-treatment did not have an effect on the drying time of bananas, however, the drying time is significantly dependant on slice thickness.

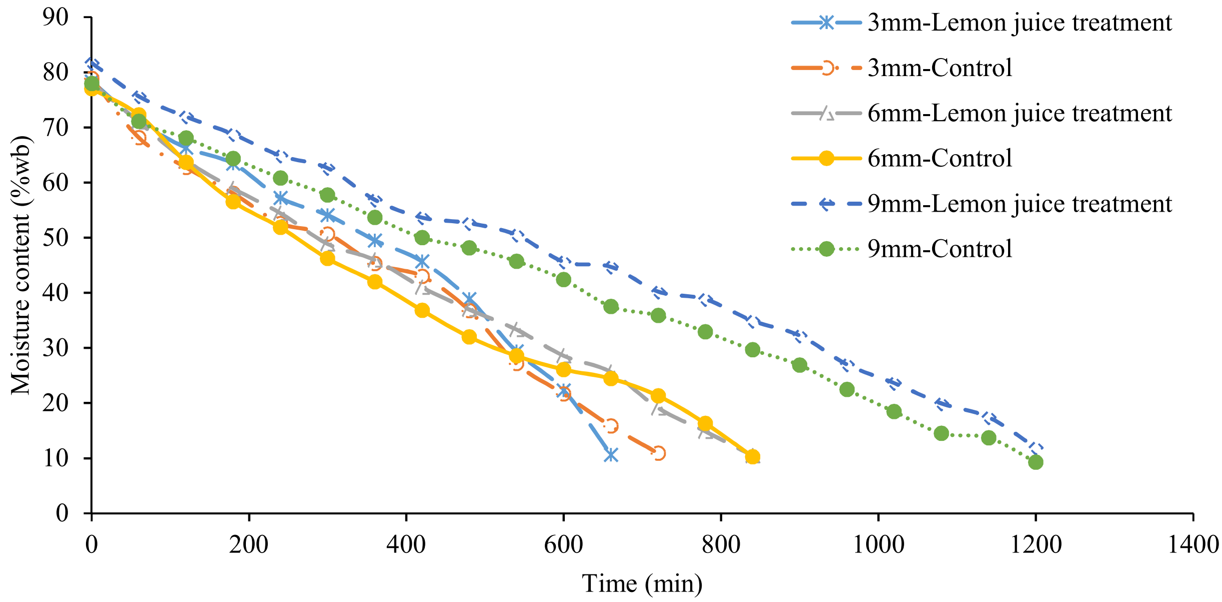
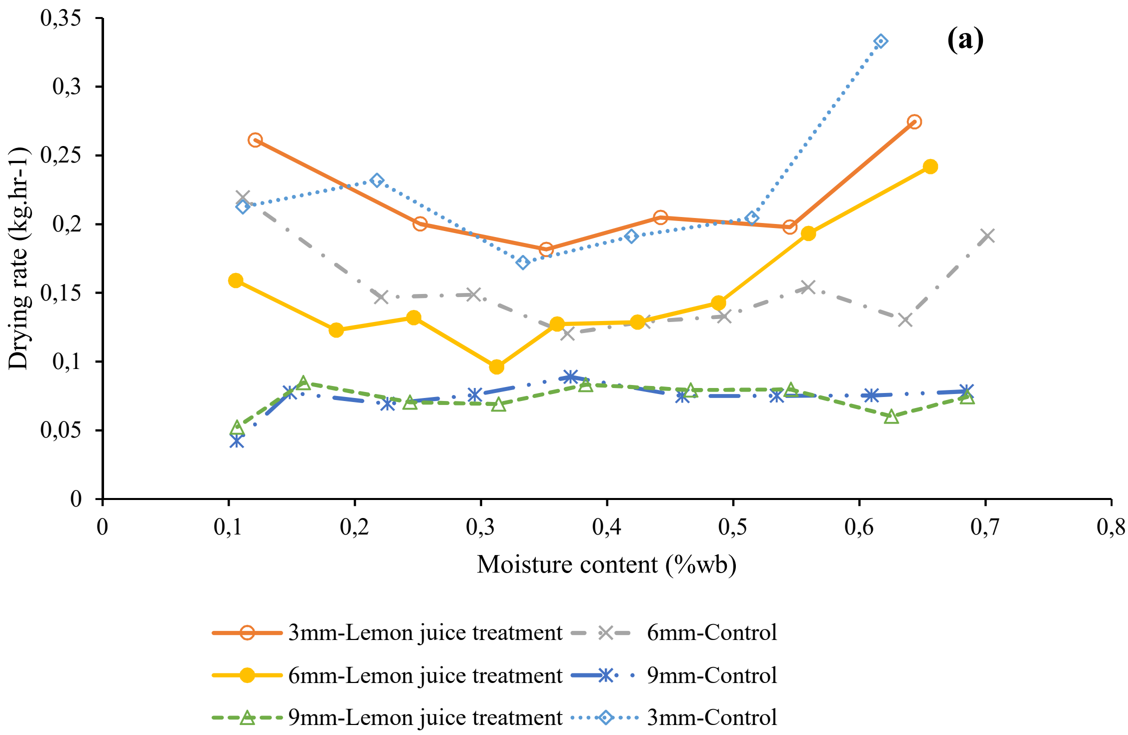


Figure 3.9 Moisture content variation of OAD during drying period

3.3.4 The effect of pre-drying treatments and slice thickness on drying rate

The drying rate varied for all drying methods, treatments and thicknesses of mango slices. Lemon juice treated and control samples of all mango thickness dried in OVD did not show a significant difference (P>0.05) in the drying rate. The maximum drying rate of 0.33g.hr^{-1} was for 3 mm lemon juice treated mango slices as shown in Figure 3.10. Observation of the maximum drying rates occurred within the first hour of drying. The mean drying rates of lemon juice treated samples was 0.19g.hr^{-1}, 0.13g.hr^{-1} and 0.065g.hr^{-1} for 3 mm, 6 mm and 9 mm thick slices, respectively. The mean drying rates for control samples was 0.19g.hr^{-1}, 0.14g.hr^{-1}, and 0.066g.hr^{-1} for 3 mm, 6 mm and 9 mm samples, respectively. The results indicate that pre-treatment did not have an effect on the drying rate of mango slices that were dried in OAD. The drying rate was higher for thinner slices (3 mm and 6 mm) and no constant drying rate period was observed for the thinner slices. The drying occurred mainly in the falling rate period, and it initially increased as moisture content reduced. This clearly indicates that the drying of 3 mm and 6 mm mango slices was driven, by the diffusion mechanism (Bebartta *et al.*, 2014; Doymaz, 2015, Olanipekun *et al.*, 2015, Onwude *et al.*, 2016). The observations of this study were consistent with those of Akoy (2014) in the thin-layer drying of mangoes, Yu *et al* (2015) in drying Chines hawthorn and Doymaz (2015) in the thin-layer drying of carrot slices. The drying rate increases in the initial stage of drying because the product is increasing its internal temperature. The air temperature is greater than the product temperature at this stage, hence, accelerating moisture removal in the mango slices (Yu *et al.*, 2015; Onwude *et al.*, 2016). The subsequent decrease in drying rate is attributed to the reduction in porosity of the mango slices because of shrinkage, which increased resistance of water movement, leading to a further decrease in drying rate. The drying rate also accelerated at the end of the drying period, because the product temperature was lower than the air temperature. The 9 mm mango slices only dried at a constant rate and a falling rate was only observed after a 20% moisture content was reached and during the last hour of drying (after the eighth hour). Several research studies have found that thicker slices dry at a relatively lower drying rate and that drying is at constant drying rate period, because of a lack of more surface area per mass of moisture. In addition, increasing the size increases the path length for mass transfer and reduces the drying rate (Bebartta *et al.,* 2015). Furthermore, gravity and capillary forces are the driving mechanisms for the constant drying rate (Onwude *et al.*, 2016). The constant temperature used for MVD might not be suitable for drying the 9 mm mango slices, by the diffusion mechanisms, which is the suitable driving mechanism that would be required for drying fruit. According to Onwude (2016), a constant drying rate may affect the surface of the product, leading to quality losses.



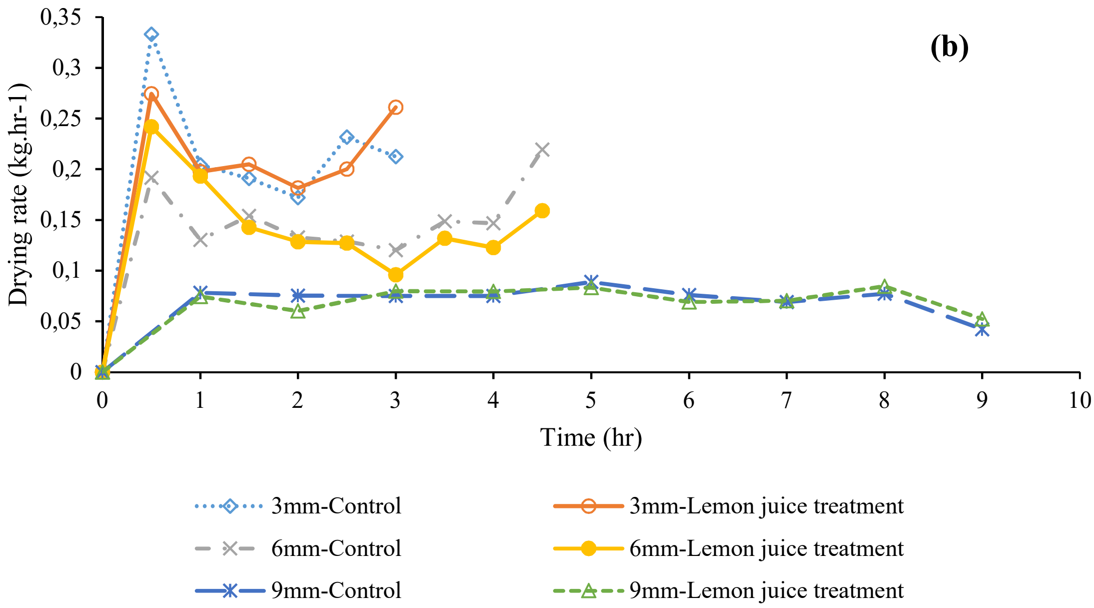


Figure 3.10 Drying rate curves (a) and (b) of mango slices during the drying period in OVD

The mean drying rates were 0.13g.hr^{-1}, 0.067g.hr^{-1} and 0.055g.hr^{-1} for 3 mm, 6 mm and 9 mm thick slices, respectively for both control and lemon juice treated samples. There was no significant difference (P>0.05). A maximum drying rate of 0.2 kg.hr^{-1} was observed for 3 mm mango slices. The maximum drying rate occurred within the first hour of drying, when the product's internal temperature was increasing. Similar observations of higher drying rates for thinner slices occurred in OVD. The falling drying rate was mainly observed, indicating that diffusion is the driving mechanism for drying in mango slices in MVD. These results are in agreement with the findings by Goyal *et al.* (2006) and Akoy (2007). In addition, it shows that diffusion is the dominant mechanism driving the moisture movement in mango slices (Rasouli *al*., 2011; Priyadarshini*et al*., 2013). Akoy (2007) indicates that for fruit, such as mangoes, the constant drying rate is either relatively small or does not exist at all

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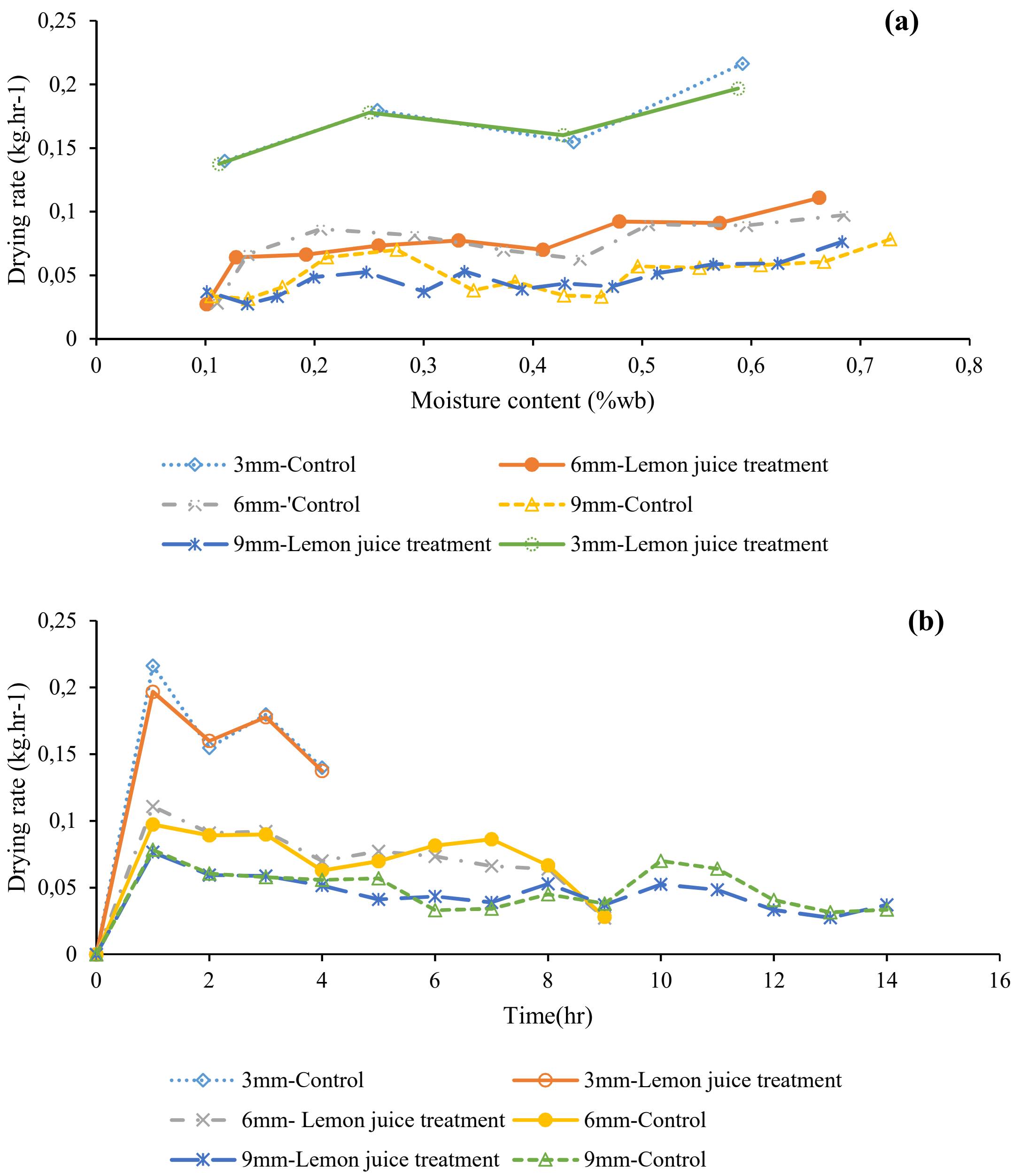


Figure 3.11 Drying rate curves (a) and (b) of mango slices during the drying period in MVD

The mean drying rates in OAD were 0.054g.hr^{-1}, 0.045g.hr^{-1} and 0.069g.hr^{-1} for 3 mm, 6 mm and 9 mm thick slices, respectively occurred for the control samples. The mean dying rates for lemon treated mango slices was 0.052g.hr^{-1}, 0.045g.hr^{-1} and 0.061g.hr^{-1} for 3 mm, 6 mm and 9 mm thick slices, respectively. There was no significant difference (P>0.05) in the drying rate of lemon juice treated as well as, for the control samples, of 3 mm, 6 mm and 9 mm thick slices. Findings show that the maximum drying rate was within the first hour of drying as shown in Figure 3.12. The drying rate was marked by falling drying rate periods for all mango thicknesses dried. Fluctuations in drying rate could be attributed to the fluctuations in temperature, relative humidity and also the wind speed could have made a significant contribution to the drying rate in OAD.

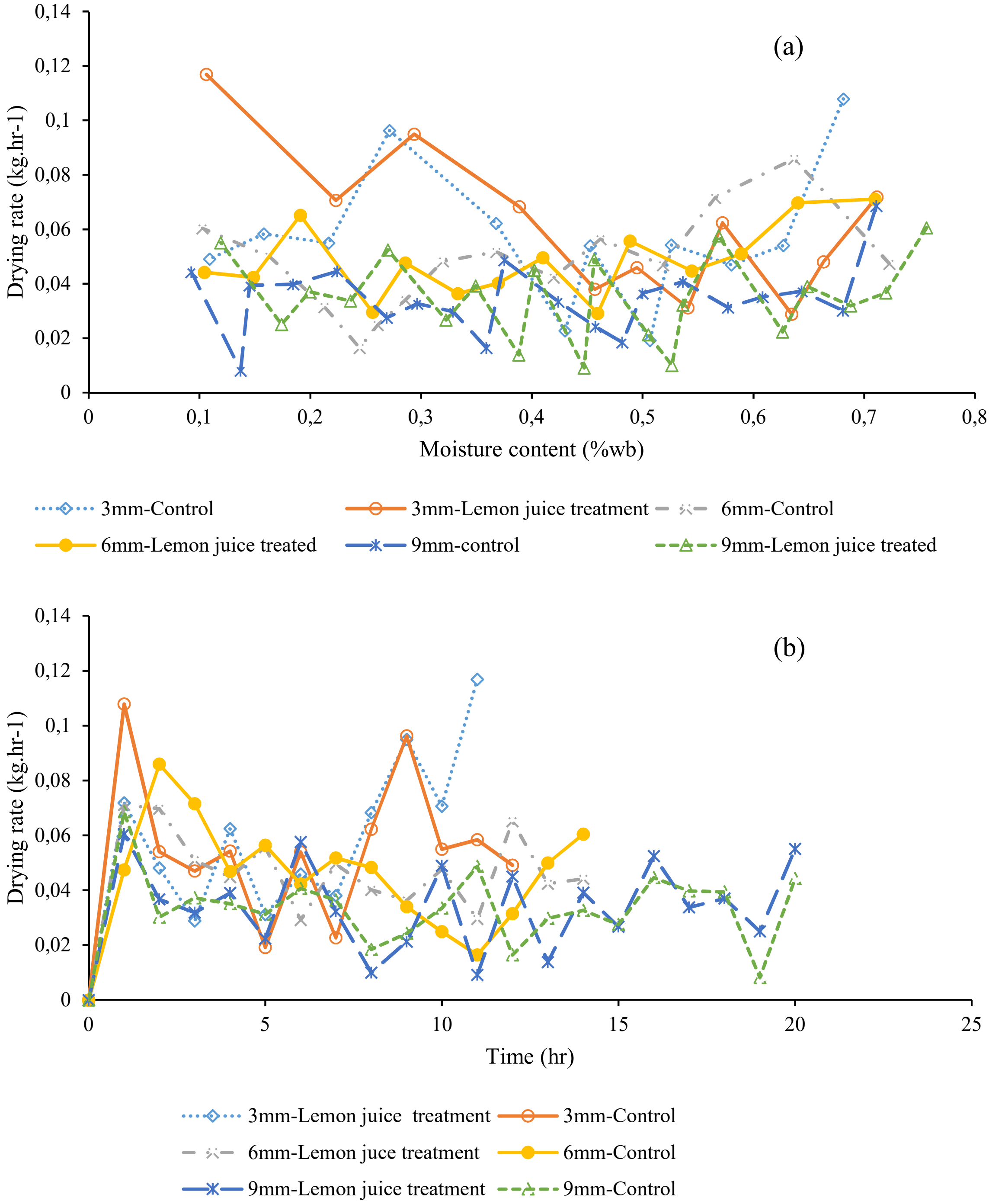


Figure 3.12 Drying rate curves (a) and (b) of mango slices during the drying period in OAD

The highest drying rate was found for OVD, which was 3% higher than MVD and 12% higher than OAD. This study finding clearly indicates that temperature, relative humidity and slice thickness had an influence in the drying rate. Constant drying conditions, such as those observed in OVD might not be suitable for drying 9 mm thick mango slices. Temperatures in MVD were more suitable, because a falling rate period was observed, during the drying process. It is clear that the use of OAD does not offer the best solution, because of the fluctuations in the drying rate, which may result in product quality losses.

3.3.5 Mathematical modelling

The dimensionless moisture content (moisture ratio) decreased, with an increase in the drying time. The moisture ratio data were used to statistically analyse drying models, namely, the Lewis, Page, Henderson and Pabis and Midilli *et al.* models. To investigate the goodness of fit, the Chi-square (x^2), coefficient of determination (R^2) and the root mean square (RMSE) were used. The comparison between experimental and predicted moisture ratio curves for all drying models show that the four drying models used give a good correlation with experimental data. The Midilli *et al.* and Page models had the highest R^2 and the lowest RMSE and/or x^2. In, OVD the R^2 for the control mango samples varied between 0.9953 and 0.9790 for the Midilli *et al.* model and it varied between 0.9954 and 0.9803 for the Page model, as shown in Table 3.11. The lemon juice treated samples in OVD, had an R^2 variation of between 0.9959 and 0.9832 for the Midilli *et al.* model and between 0.9949 and 0.9815 for the Page model, as shown in Table 3.12. Mango slices dried in OAD had an R^2 value that was between 0.9957 and 0.9662 for Midilli *et al.* and for the Page model the R^2 varied between 0.9981 and 0.9550 for the lemon juice treated and control samples, respectively. In MVD, the Midilli *et al.* model had R^2 variations between 0.9929 and 0.9981 for the lemon juice treated and control samples, respectively and for the Page model, R^2 varied between 0.9942 and 0.9815 for the lemon juice treated and control samples, respectively. The highest correlation was for the control samples in OAD and lemon juice treated samples in OVD and MVD. In essence, the Midilli *et al.* and the Page models are useful for predicting the moisture ratio of drying mango slices. The Henderson and Pabis model, unlike the Lewis model, had the lowest correlation of the experimental data. Observations of the moisture ratio curves, as shown in Figure 3.13-3.15.on all drying methods indicated that the Henderson and Pabis model over-predicts the moisture ratio at the beginning of the drying period and the Lewis model over-predicts at the end of the drying period. Workneh and Oke (2012) made similar observations in microwave drying.

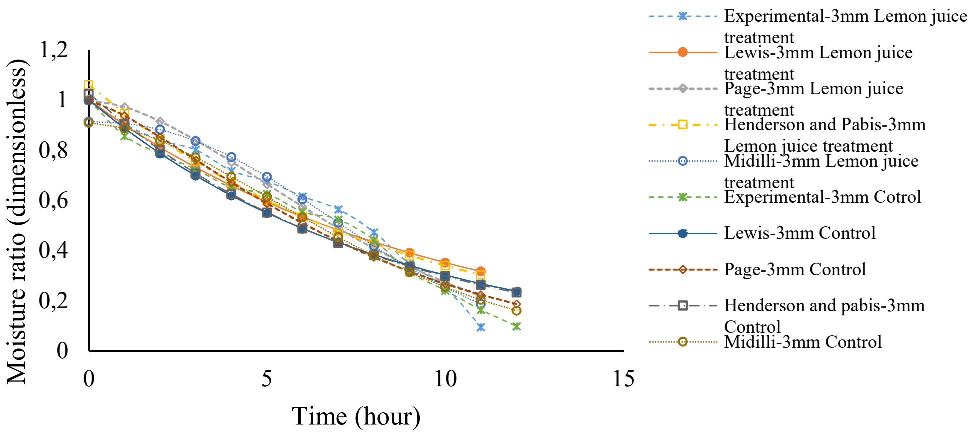
A comparison of the experimental and predicted moisture ratios in Figure 3.16 (a, b and c) shows that the Midilli *et al.* model provides the best correlation for drying mango slices, using OVD, OAD and MVD. Therefore, in the drying of mango slices, the model is representative of the drying data. Similar outcomes were observed in drying mangoes using a microwave oven (Nazmi *et al.*, 2017), where Midilli *et al.* model was the best representative for predicting the moisture ratio. Similarly, the Abano *et al.* (2013) findings show that the Midilli *et al.* model has the best prediction in hot air drying of treated and untreated mangoes and that it is better than the Page model. Simal *et al.* (2005), Azoubel *et al*. (2010), Abano *et al*. (2013), Longhmanieh and Bakhoda (2013) found this model to be accurate when drying kiwis, bananas, mangoes and thyme leaves respectively.

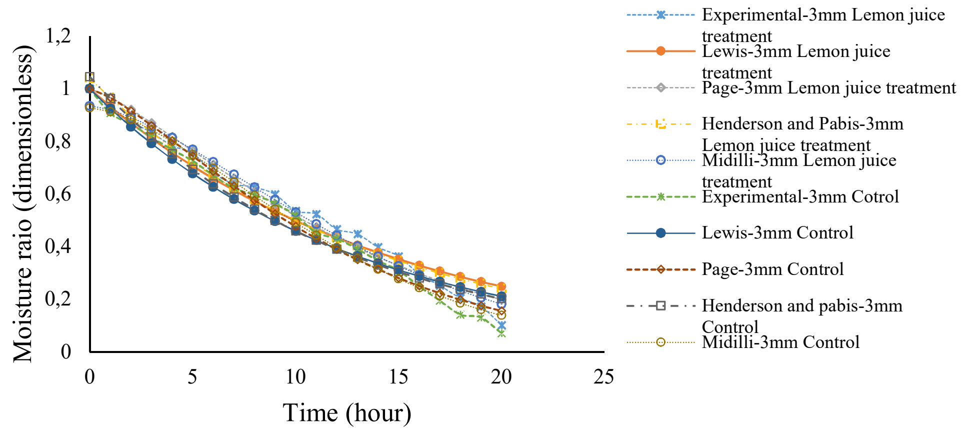
Table 3.2 Statistical parameters of different drying models tried for the control mango samples of various thickness

Model	Thickness (mm)	Model constants				x^2	R^2	RMSE
		k (hr^{-1})	**n**	**a**	**b**			
Lewis- OVD	3mm	0.5152	-	-	-	6.1147×10^{-7}	0.9705	0.00072
	6mm	0.3229	-	-	-	0.01094	0.9882	0.09924
	9mm	0.1604	-	-	-	0.00057	0.9656	0.02245
Lewis- OAD	3mm	0.1199	-	-	-	1.0641×10^{-5}	0.9413	0.00312
	6mm	0.1151	-	-	-	0.00017	0.9972	0.01286
	9mm	0.0777	-	-	-	3.1926×10^{-5}	0.9643	0.00551
Lewis-VMD	3mm	0.3970	-	-	-	3.1606×10^{-6}	0.9730	0.00154
	6mm	0.1833	-	-	-	9.3369×10^{-6}	0.9743	0.00911
	9mm	0.1172	-	-	-	1.9517×10^{-5}	0.9684	0.00425
Page-OVD	3mm	0.4406	1.2637	-	-	0.00038	0.9803	0.01653
	6mm	0.2211	1.3778	-	-	0.02142	0.9856	0.13090
	9mm	0.0733	1.5085	-	-	0.00037	0.9954	0.01716
Page-OAD	3mm	0.0648	1.3099	-	-	0.00197	0.9577	0.04050
	6mm	0.0875	1.1330	-	-	0.00049	0.9957	0.00049
	9mm	0.0348	1.3273	-	-	0.00177	0.9800	0.03998
Page-VMD	3mm	0.2773	1.4005	-	-	0.00026	0.9910	0.01145
	6mm	0.0983	1.3790	-	-	0.00042	0.9907	0.01816
	9mm	0.0607	1.3162	-	-	0.00105	0.9815	0.03006
Henderson and Pabis-OVD	3mm	0.5306	-	1.0248	-	0.00032	0.9687	0.01343
	6mm	0.3418	-	1.0461	-	0.01947	0.9862	0.12483
	9mm	0.1749	-	1.0720	-	0.00054	0.9591	0.02040
Henderson and Pabis-OAD	3mm	0.1239	-	1.0254	-	0.00042	0.9388	0.01880
	6mm	0.1202	-	1.0351	-	4.5775×10^{-5}	0.9931	0.00626
	9mm	0.0821	-	1.0453	-	0.00068	0.9603	0.02468
Henderson and Pabis-MVD	3mm	0.4111	-	1.0317	-	0.00058	0.9707	0.01705
	6mm	0.1951	-	1.0545	-	0.00056	0.9701	0.02082
	9mm	0.1238	-	1.0468	-	0.00062	0.9646	0.02311
Midilli *et al.*-OVD	3mm	0.4071	1.3348	0.9735	0	9.8458×10^{-5}	0.9814	0.00649
	6mm	0.1782	1.5255	0.9570	0	0.02177	0.9790	0.11431
	9mm	0.0526	1.6314	1.6314	0	2.6825×10^{-5}	0.9953	0.00386
Midilli *et al.*-OAD	3mm	0.0257	1.6962	0.9092	0	0.000106	0.9665	0.00839
	6mm	0.0894	1.1251	1.0039	0	1.4651×10^{-6}	0.9981	0.00102
	9mm	0.9277	1.5806	0.9277	0	9.5974×10^{-5}	0.9852	0.98520
Midilli *et al.*-MVD	3mm	0.2663	1.4287	0.9883	0	0	0.9913	0.00563
	6mm	0.0817	1.4662	0.9704	0	5.9059×10^{-5}	0.9916	0.00573
	9mm	0.0395	1.4843	0.9466	0	0.00012	0.9842	0.00901

Table 3.3 Statistical parameters of different drying models tried for the lemon juice treated mango of various thickness

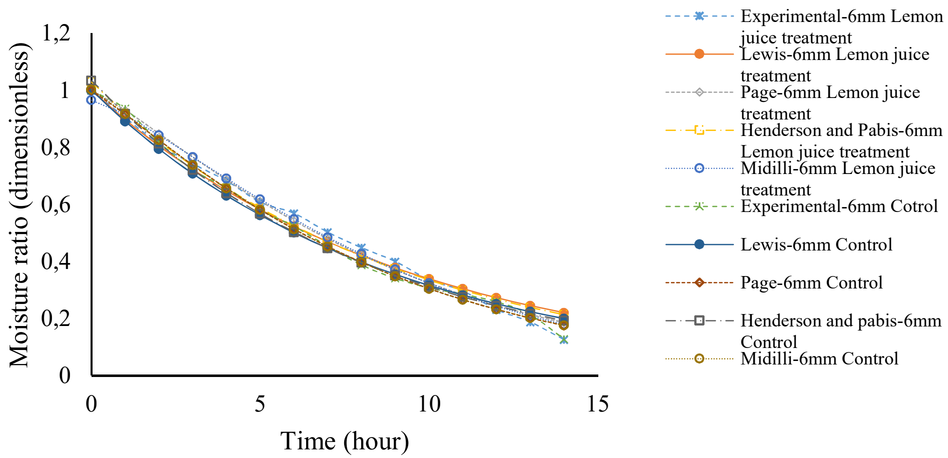
Model	Thickness (mm)	Model constants				x^2	R^2	RMSE
		k (hr^{-1})	**n**	**a**	**b**			
Lewis- OVD	3mm	0.4783	-	-	-	0.00052	0.9633	0.02130
	6mm	0.2714	-	-	-	0.00859	0.9689	0.08791
	9mm	0.1634	-	-	-	0.00061	0.9647	0.02319
Lewis- OAD	3mm	0.1045	-	-	-	0.00066	0.9089	0.02449
	6mm	0.1081	-	-	-	2.5591×10^{-5}	0.9884	0.00487
	9mm	0.0695	-	-	-	0.00194	0.9635	0.04297
Lewis-VMD	3mm	0.3934	-	-	-	1.7272×10^{-5}	0.9694	0.00359
	6mm	0.1989	-	-	-	1.7186×10^{-5}	0.9827	0.00391
	9mm	0.1213	-	-	-	1.0145×10^{-5}	0.9774	0.00307
Page-OVD	3mm	0.3714	1.3724	-	-	0.00037	0.9821	0.01634
	6mm	0.2048	1.3889	-	-	0.00059	0.9815	0.02166
	9mm	0.0637	1.5573	-	-	0.00043	0.9949	0.01822
Page-OAD	3mm	0.0282	1.6637	-	-	0.00283	0.9550	0.04810
	6mm	0.0072	1.1963	-	-	0.00033	0.9901	0.01744
	9mm	0.0334	1.2945	-	-	0.00126	0.9772	0.03370
Page-MVD	3mm	0.2583	1.4675	-	-	0.00026	0.9927	0.01140
	6mm	0.1213	1.3078	-	-	0.00029	0.9942	0.01523
	9mm	0.0673	1.2852	-	-	0.00013	0.9897	0.01078
Henderson and Pabis-OVD	3mm	0.4914	-	1.0381	-	0.00025	0.9614	0.01348
	6mm	0.3236	-	1.0473	-	0.00028	0.9581	0.01486
	9mm	0.1788	-	1.0763	-	0.00063	0.9577	0.02208
Henderson and Pabis-OAD	3mm	0.1139	-	1.0609	-	0.00037	0.9017	0.01761
	6mm	0.1123	-	1.0297	-	0.00019	0.9824	0.01272
	9mm	0.0732	-	1.0396	-	0.00035	0.9602	0.01785
Henderson and Pabis-MVD	3mm	0.4096	-	1.0376	-	0.00069	0.9665	0.01867
	6mm	0.2093	-	1.0463	-	0.00052	0.9796	0.02107
	9mm	0.1276	-	1.0439	-	0.00056	0.9741	0.02188
Midilli *et al.*-OVD	3mm	0.3369	1.4607	0.9722	0	6.8307×10^{-5}	0.9832	0.00541
	6mm	0.1643	1.5382	0.9584	0	5.0239×10^{-5}	0.9836	0.00549
	9mm	0.0512	1.6609	0.9708	0	3.0819×10^{-5}	0.9959	0.00414
Midilli *et al.*-OAD	3mm	0.0077	2.2222	0.9138	0	7.9418×10^{-5}	0.9662	0.00711
	6mm	0.0559	1.2903	0.9659	0	3.1126×10^{-5}	0.9932	0.00472
	9mm	0.0166	1.5322	0.9351	0	5.9648×10^{-5}	0.9818	0.00691
Midilli *et al.*-MVD	3mm	0.2475	1.4978	0.9883	0	0	0.9929	0.00548
	6mm	0.0604	1.6372	0.8888	0	6.7893×10^{-6}	0.9981	0.00194
	9mm	0.0478	1.4193	0.9536	0	8.2897×10^{-5}	0.9903	0.00769





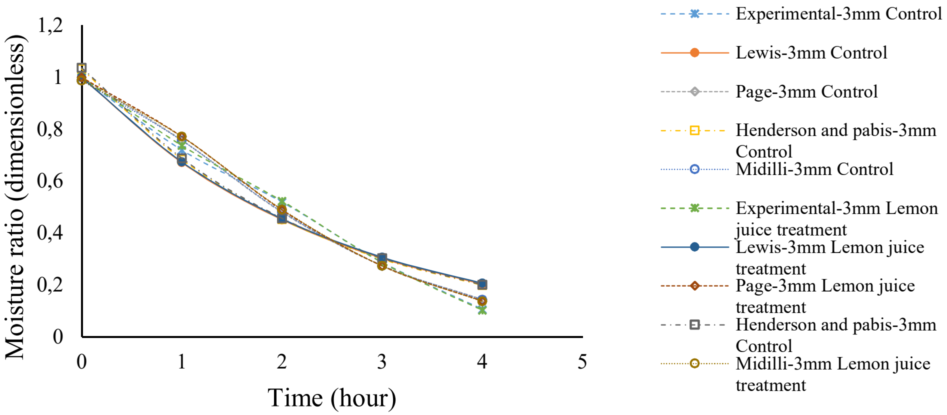
(b) 6mm thickness

(a) 3mm thickness

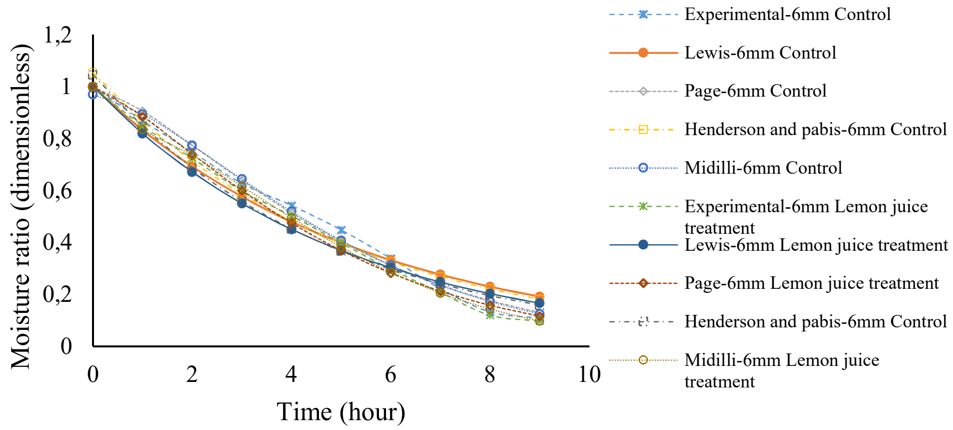


(c) 9mm thickness

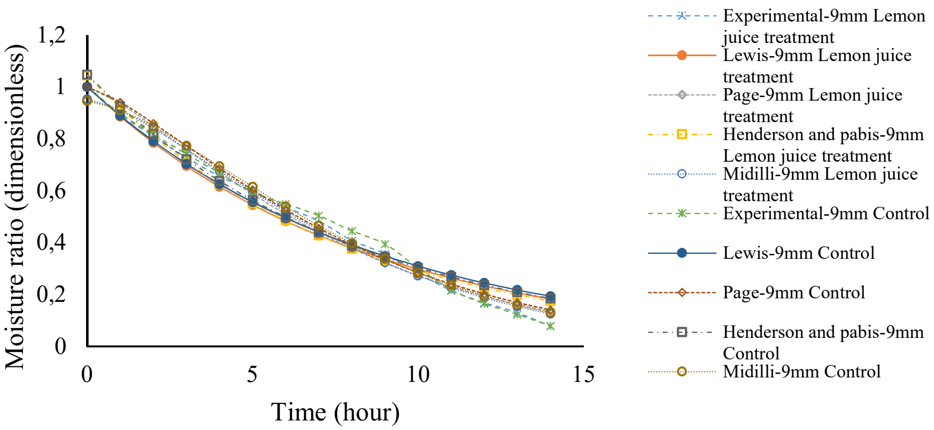
Figure 3.13: Moisture ratio variation with drying time for (a) 3mm, (b) 6mm and (c) 9mm thickness mango dried in OAD



(a) 3mm thickness

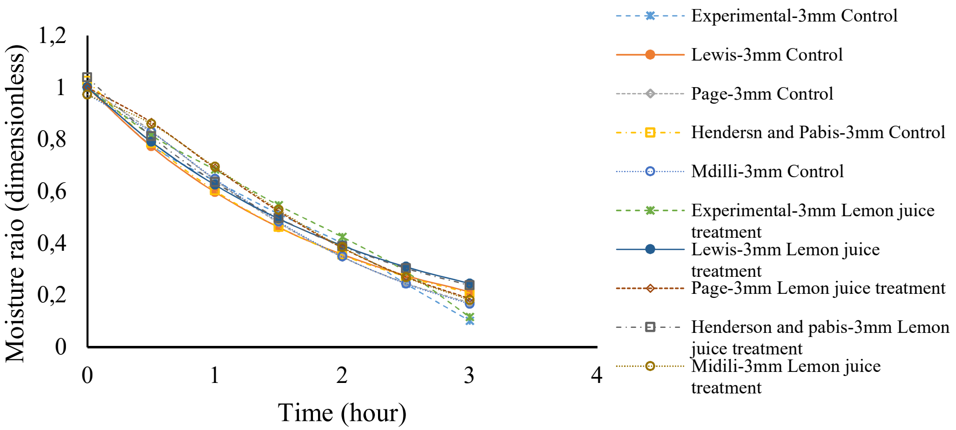


(b) 6mm thickness

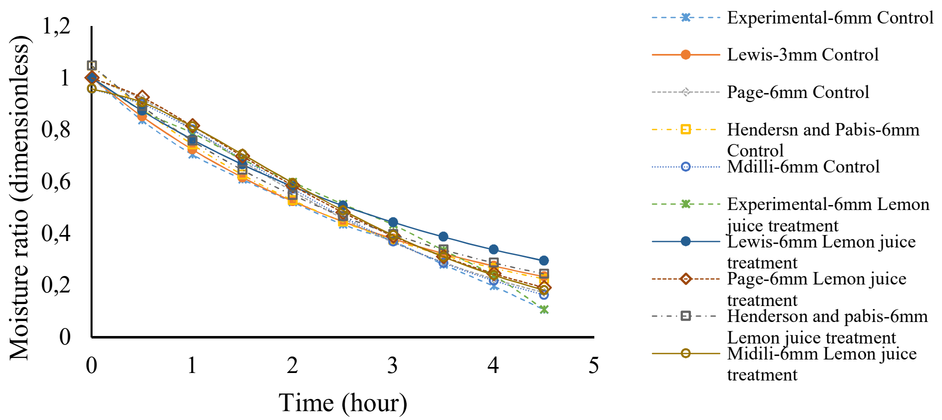


(c) 9mm thickness

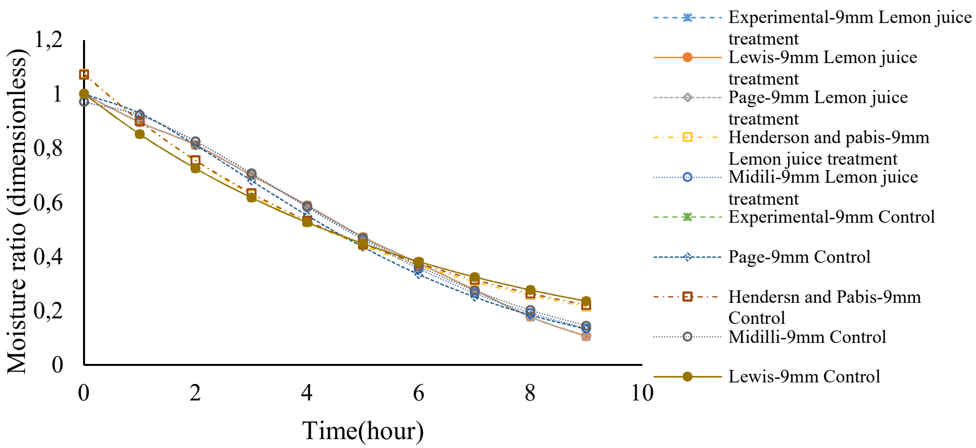
Figure 3.14 Moisture ratio variation with drying time for (a) 3mm, (b) 6mm and (c) 9mm thickness mango dried in MVD



(a) 3mm thickness

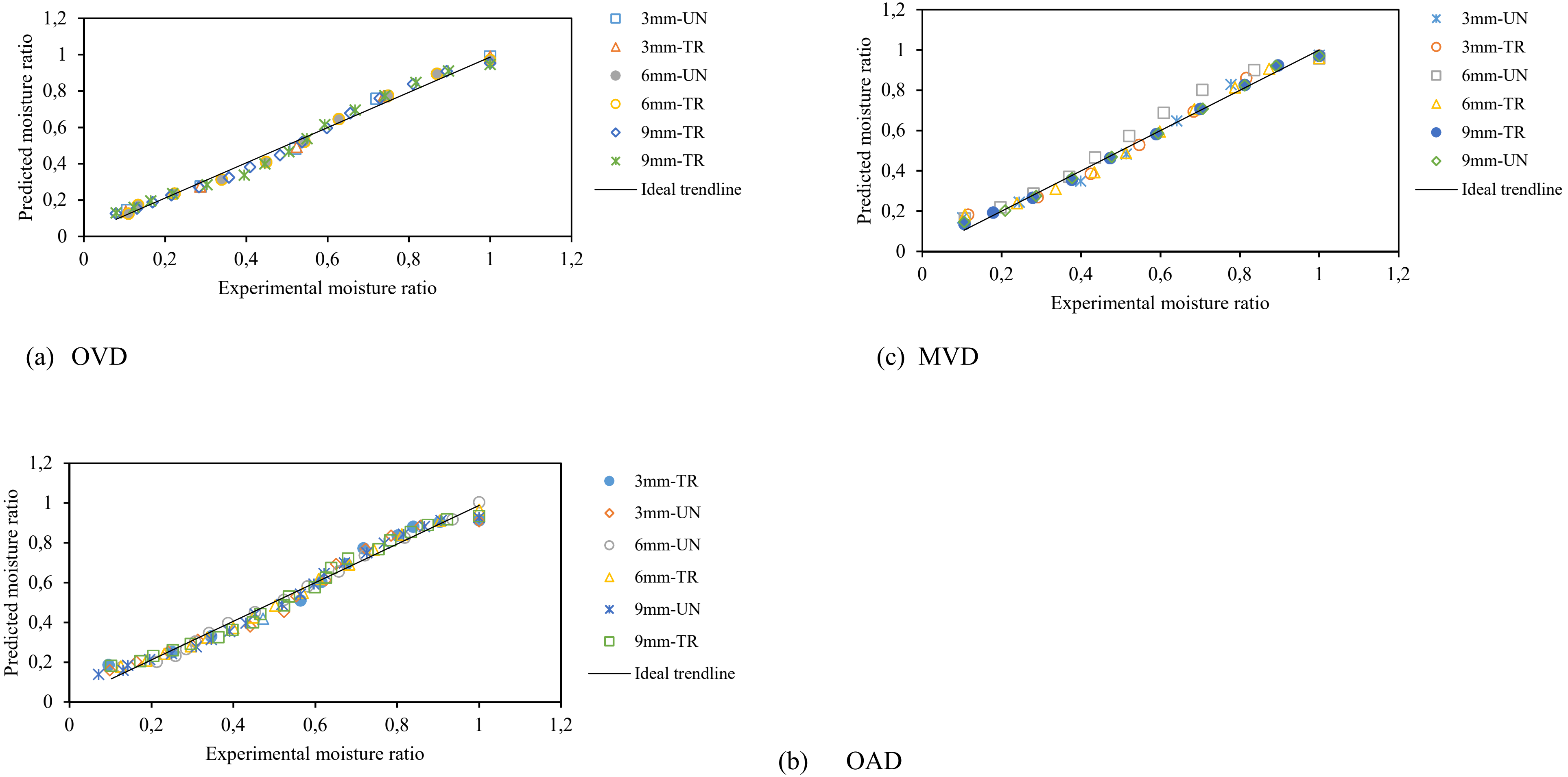


(b) 6mm thickness



(c) 9mm thickness

Figure 3.15 Moisture ratio variation with drying time for (a) 3mm, (b) 6mm and (c) 9mm thickness mango dried in OVD



(a) OVD

(c) MVD

(b) OAD

Figure 3.16 Experimental vs. predicted moisture ratio of Midilli *et al.* model for (a) OVD, (b) OAD and (c) MVD

3.3.6 Estimation of the effective moisture diffusivity

The moisture transfer during drying was governed by diffusion. Therefore, Fick's second law of diffusion was used to predict the effective moisture diffusion rate of lemon juice treated and control mango of different thickness dried in OAD, OVD and MVD. The variation of ln(MR) with drying time, for the Midilli *et al*. model indicates that the graph generally has a negative slope, as shown in Appendix 3.2. The effective moisture diffusivity varied between 1.048×10^{-8} $m^2.s^{-1}$ and 9.7547×10^{-9} $m^2.s^{-1}$ as seen in Tables 3.4 and 3.5. The effective moisture diffusivity varied with mango thickness; a 3 mm thickness had a higher moisture diffusivity than, 6 mm and 9 mm thick slices. However, no significant ($P>0.05$) difference in moisture diffusivity was observed for lemon juice treated and control samples. In addition, OVD demonstrated higher effective moisture diffusivity (D_{eff}) than OAD and MVD. This could be attributed to that OVD was conducted at relatively higher drying temperature, compared to the other drying methods (Fan *et al*., 2015). The effective moisture diffusivity obtained in this study was within the range found in research studies for hot air drying methods. Vega-Falvez *et al.* (2007) found a moisture diffusivity range of $5.30\text{-}17.173 \times 10^{-10}$ $m^2.s^{-1}$ for aloes and a diffusivity range between $1.345\text{-}2.658 \times 10^{-9}$ $m^2.s^{-1}$ was found onion slices (Lee and Kim, 2008), for thyme Doymaz (2010) found an effective moisture diffusivity ranging between 1.097 $m^2.s^{-1}$ and 5.991×10^{-9} $m^2.s^{-1}$. Studies on mango drying found a moisture diffusivity range of $1.80 \times 10^{-10}\text{-}2.22 \times 10^{-10}$ (Abano *et al*., 2013). According to Zogzas *et al*. (1996) the acceptable range of effective moisture diffusivity is between 10^{-12} $m^2.s^{-}$ and 10^{-8} $m^2.s^{-1}$. This study has demonstrated that the moisture diffusivity is strongly influenced by the method of drying and the thickness of the drying material (Abano *et al*., 2013; Shi *et al.*, 2013). Studies by Perumal (2007) came to the similar conclusion that open-air uncontrolled solar drying has a lower effective moisture diffusivity, compared to other drying methods, including hot air methods and that a thicker material has a lower moisture diffusivity than thinner material.

Table 3.4 Effective moisture diffusivity of lemon juice treated samples

Drying method	Thickness(mm)	Slope	D_{eff} ($m^2.s^{-1}$)
OVD	3	-0.0107	9.7547×10^{-9}
	6	-0.0071	6.4727×10^{-9}
	9	-0.0039	3.55545×10^{-9}
OAD	3	-0.0027	2.46147×10^{-9}
	6	-0.0022	2.00564×10^{-9}
	9	-0.0015	1.36748×10^{-9}
MVD	3	-0.0091	8.29605×10^{-9}
	6	-0.0044	4.04774×10^{-9}
	9	-0.0027	2.46748×10^{-9}
LSD			7.50143×10^{-9}
CV%			75.3
P			0.489

Table 3.5 Effective moisture diffusivity of control samples

Drying method	Thickness(mm)	Slope	D_{eff} ($m^2.s^{-1}$)
OVD	3	-0.0115	1.0484×10^{-8}
	6	-0.0074	6.74624×10^{-9}
	9	-0.039	3.55500×10^{-9}
OAD	3	-0.0028	2.55263×10^{-9}
	6	-0.0022	2.00564×10^{-9}
	9	-0.0018	1.64100×10^{-9}
MVD	3	-0.0090	8.20489×10^{-9}
	6	-0.0042	3.82895×10^{-9}
	9	-0.0027	2.46100×10^{-9}
LSD			7.50143×10^{-9}
Cv%			75.3
P			0.489

3.3.7 Conclusions

Three drying methods were evaluated to determine the drying characteristics, the drying models that best fit the drying data and to estimate the effective moisture diffusivity. OAD occurred at the ambient air conditions (15.5-33.2˚C) and a 15.5-38% relative humidity, MVD at average an average temperature of 49.3˚C and 23.58% RH. OVD was set at 70˚C. OAD took three days (eight hours of drying per day) to complete drying, MVD took 13 hours to complete drying, OVD took nine hours and OAD took 20 hours. It was found that lemon juice treatment did not have an effect on the drying characteristics. The thickness of the mango slices had a significant effect on the drying characteristics, such as drying time and drying rate. The 3 mm mango slices dried faster in OVD than in MVD and OAD, respectively, compared to the 6 mm and 9 mm thick slices. This was attributed to a relatively high temperature in OVD and MVD, which increased the drying rate. Furthermore, the drying rates were higher for thinner slices because of the increased surface area for moisture evaporation. Consequently, the moisture diffusivity was relatively higher for 3 mm mango slices than for 6 mm and 9 mm. Drying at constant temperature as in OVD is not practical for 9 mm mango slices, because drying takes place at the constant drying rate period. Although, MVD had longer drying time, the moisture removal rate was relatively higher and drying occurred at the falling rate-drying period, enabling moisture removal by diffusion and this resulted in better product quality. Therefore, the temperatures within MVD are suitable for drying mangoes of different thickness, simultaneously. Furthermore, MVD showed better drying characteristics than OAD in drying mango fruit. MVD is, therefore, a practical method for use in the drying of large quantities of a product and it allows for the use of renewable energies such as solar energy as an alternative to electricity. Therefore, it eliminates the challenges experienced due to the use of energy-intensive drying methods. This study found the Midilli *et al.* model to be the best fit to the experimental moisture ratio data, while the Page model can also be used to estimate the moisture ratio of mango fruit during drying.

3.4 References

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4. THE EFFECTS OF THIN-LAYER HOT AIR DRYING METHODS ON QUALITY OF MANGO SLICES

Abstract

Fresh Tommy Atkin mangoes (*Mangifera indica L.*) with flesh colour parameters, of L*(47.70±5.6), a* (24.72±6.9) and b*(34.87±8.76), a mean TSS of 13.85±2.07°Brix and firmness of 4.4±3.2N were used for the drying experiments. This study investigated the effect of three drying methods, namely, open-air solar drying (OAD), a modified ventilation solar dryer (MVD) and a convective oven dryer (OVD) on quality parameters of 3 mm, 6 mm and 9 mm mango slices with and without lemon juice pre-treatment. The study observations found relatively higher colour changes (ΔE) for mango slices dried in OAD than for MVD and OVD, respectively. Lemon juice treatment did not affect the colour parameters L* and a*, but only the drying method and the mango slice thickness affected the colour. It was found that the thicker mango slices (9 mm) dried in OAD became darker, indicating that there was more browning, compared to the thinner slices (3 mm and 6 mm) in MVD and OAD. Furthermore, pre-treatment did not affect the rehydration ratio; however, thicker slices dried in OAD showed a higher rehydration ratio, indicating cell damage. This was evident with microstructure analysis by Scanning Electron Microscopy (SEM) that showed significant cracking and pore formation in OAD dried mangoes. Sensory evaluations showed that panellists preferred treated mango samples. The overall acceptability of treated mangoes dried with MVD (7.09±1.26) was not significantly higher ($P>0.05$) than that of mangoes dried in OVD (6.94±1.64) and OAD (6.51±2.07), respectively. In addition, the microbial counts showed that the dried mangoes were safe for human consumption, because pathogens were not detected. However, fungi and anaerobic bacteria counts found were higher than the international stipulated limit of $1x10^3$ $CFU.g^{-1}$.

Keywords: *Solar, drying, thickness, pre-treatment, colour, microbial count, sensory evaluation, microstructure*

4.1 Introduction

Mango (*Mangiferia Indica L.*) is an important tropical and subtropical fruit that is popular on the world market because of its unique and attractive flavour, colour and nutritional value. It has the potential to provide about 50% of the recommended daily intake of Vitamin C (Akoy, 2007; Djioua *et al.*, 2012). However, the perishable nature of this fruit and the short harvest season limit its utilization for both economic and nutritional benefits. As a result, mangoes are not well developed as a commercial and export crop (Akoy, 2007). Dried mango is becoming a preferred health snack, which has a potential for export. The availability of a wide variety of dried fruit to consumers has resulted in a concern over the quality standards (Fudholi *et al.*, 2011).

Studies have clearly shown that the method of drying has a significant impact on the quality of the dried produce. Several methods of drying have result in the loss of chemical, physical and sensory quality as well as microbial changes. Mensah *et al.* (2002) and de Souse (2008) found that food-borne illnesses, because of food processing procedures such as drying are a major international problem and continue to be a concern in developing countries, such as South Africa. This is a result of the food standards, regulations and safety policies, which are not well established or not in place. The quality of dried fruit is categorized as chemical, physical and sensory (Sivakumar *et al.*, 2011). In addition, the assumption has always been that low moisture foods (LMF) prohibit microbial growth (Ntuli *et al.*, 2017). However, counts of bacterial and fungal pathogens higher than the stipulated international limits ($<10^3$ CFU.g^{-1}) have been observed in dried fruit produced at both a commercial and household level (Barth *et al.*, 2010; Ntuli *et al.*, 2017).

Drying is a simultaneous heat and mass transfer process and during the drying process internal stresses in the food result in physical changes, such as cell collapse and shrinkage, colour changes and loss of rehydration ability (Lewicki and Pawlak, 2003; Karim, 2005; Perumal, 2007; Karim *et al.*, 2008). The acceptance of dried fruit can be assessed by its retention of quality, and to enhance this, different pre-treatments have been developed for fruit dehydration, including sulphating, blanching and fruit juice (Karim, 2005). Pre-treatments inhibit the enzymatic and non-enzymatic darkening of dried fruit (Levi *et al.*, 1980). Studies by Karim *et al.* (2008) found that pre-treated samples exhibit less darkening, and panellists have judged in favour of pre-treated samples for the dried pineapple. Masamba *et al.* (2013) further found that pre-treatment significantly improves colour and flavour. Furthermore, pre-treatment accelerates the drying process and prevents browning (Jayaraman and Gupta, 2006). Sensory evaluation studies have shown that lemon-treated mangoes are preferred to salt- treated mangoes (Abano *et al*., 2013).

The hot air drying methods used for fruit play a significant role in quality parameters (Perumal, 2007). Open-air uncontrolled solar drying is a popular method used for preservation in hot climates, such as South Africa, rather than canning, mainly due to energy savings of solar energy, and it is a result of the scarcity of suitable cooling and storage facilities (Koyuncu, 2007). Perumal (2007) highlighted that the quality of product dried using the open-air uncontrolled method deteriorates to levels that are not suitable for human consumption. Investigations into convective oven drying found that a lower drying temperature of about 60°C and longer drying periods results in higher total colour changes (ΔE) and a lower dehydration ratio of mangoes (Akoy, 2007). Vadivambal *et al.* (2007) and Contreras *et al.* (2008) indicate that convective oven drying is widely used in industrial drying and research studies have reported quality loses with respect to flavour, colour and case hardening because of the use of hot air. Convective oven drying at 70-90°C is one of the drying methods that causes the degradation of important flavour compounds and colour alterations (Antal *et al.*, 2015). Consequently, massive quality losses due to open air solar drying, coupled with relatively higher energy costs of convective oven drying methods have resulted in consideration of other drying methods, such as the use of a greenhouse solar dryer, with modified ventilation. The concept of using solar energy for drying is becoming increasingly feasible because of the concern about the depletion of fossil fuels and their effect on the climate (Perumal, 2007).

Several studies have investigated the use solar drying of mangoes, including the Amelie and Kent mangoes using a greenhouse type solar dryer (Rankins *et al*., 2008; Prakash and Kumar, 2014). Tommy Atkin is a popular mango variety found in South African markets. Limited studies have been conducted on the quality parameters of Tommy Atkin mangoes dried by solar drying, open-air uncontrolled solar drying and a convective oven dryer. Furthermore, there is a lack of information on the effect of pre-treatments on the quality parameters of Tommy Akin mangoes. Therefore, this study aims to fill a research gap by investigating changes in colour, sensory properties, microbial load and microstructure of fresh Tommy Atkin mangoes slices dried using three hot air drying methods namely; OAD, MVD and OAD.

4.2 Materials and Methods

4.2.1 Fruit firmness

A penetrometer of the brand Instron ® 3345 Universal Testing Machinw (Instron, UK), with a 5kN loading capacity was used to determine the firmness of fresh mangoes. The firmness was determined by using a 4 mm stainless steel probe attached to a load cell at a penetration rate of 0.2 mm. s^{-1} and a penetration depth of 10 mm (Barrett *et al*., 2010).

4.2.2 Total soluble solids

The Total Soluble Solids (TSS) was measured by a handheld refractometer (Atago, PAL-3, Japan). The refractometer was calibrated by distilled water at room temperature. To take the TSS measurements, a 10g sample of fresh mango was homogenized to form a pulp. The fruit pulp was placed on the refractometer and measurements were taken in triplicate.

4.2.3 Colour

Colour measurements of fresh and dried fruit was done using the Hunterlab Colourflex ® EZ colorimeter (Hunter Associates laboratory, Inc., USA). The instrument was calibrated with a black and a white standardization tile before taking measurements (Ismail and Nagy, 2012; Akoy, 2014). The skin and flesh colour of fresh mangoes was determined. Fresh and dried mangoes of 3 mm, 6 mm and 9 mm thickness (treated and control) were placed on the cover glass cup of the colorimeter to cover so that the light did not escape from the instrument when taking measurements. The L^* refers to the lightness of the sample and ranges from black (zero) to white (100), a^* indicates the range of colours red (+) and green (-) and b^*, indicates the range of colours yellow (+) and blue (-) (Maskan, 2001). The total colour change (ΔE) and hue angle (H) were calculated from L*, a* and b* values using Equations 4.1-4.5 to describe the colour change during drying (Maskan, 2001; Pathare *et al*., 2013; Akoy 2014).

$$\Delta E = \sqrt{(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2} \qquad (4.1)$$

$$Hue\ angle = tan^{-1}\left(\frac{b}{a}\right) \qquad (4.2)$$

The following equations used in specifying the change in the colour parameters after drying with respect to the fresh product, as described by Akoy (2014).

$$\Delta a^* = a^*_{dried} - a^*_{fresh} \qquad (4.3)$$

$$\Delta b^* = b^*_{dried} - b^*_{fresh} \qquad (4.4)$$

$$\Delta L^* = L^*_{dried} - L^*_{fresh} \qquad (4.5)$$

4.2.4 Rehydration

Rehydration characteristics are used to indicate the physical and chemical changes that occur during drying. A dried sample (5g) was soaked in a 250 ml beaker containing 150 ml of boiling distilled water. The content was left for five minutes for the mango slices to rehydrate (Prakash *et al.*, 2004; Akoy, 2014). The water was filtered through filter paper and the rehydrated mass of the mango slices was measured in triplicate. The rehydration ratio was estimated, by using Equation 4.6:

$$Rehydration\,ratio = \frac{W_2}{W_1} \qquad (4.6)$$

The weight, W_2 (g), is the weight of the drained material and W_1 (g) is the weight of the dried material (Akoy, 2014).

4.2.5 Sensory evaluation

A group of 55 untrained panellists comprising of students and staff of the University of KwaZulu-Natal carried out a sensory evaluation of the mango samples. They were females and males of 18 years and above who evaluated the dried mango samples in terms of colour, flavour, and overall acceptability. The sensory evaluation was done at the Food Science laboratory of the university, in groups of 10 panellist at a time and they were separated by booths. Ethical clearance was obtained from the University of KwaZulu-Natal, Humanities and Social Sciences Research Ethics Committee (Reference No: HSS/0307/017M) before the panellists were recruited (Appendix B1). Samples were served randomly on plates, and they were blind-labelled with three-digit random numbers generated, by using Microsoft Office

Excel. The panellists evaluated and scored the dried mango on a nine-point hedonic rating scale. The nine points ranged from "extremely desirable" (nine point) to "extremely undesirable" (one point) (Barrett *et al.*, 2010; Okoth *et al.*, 2013; Ray *et al*. 2014; Ngamchuachit *et al.*, 2015). Panellists were permitted to use only one-digit scores on a sample evaluation card for rating (Appendix B2). The average of individual scores represented the sensory score of the dried mango sets evaluated.

4.2.6 Microbial analysis

Microbial enumeration and isolation was done in selective media. A 10 g sample of fresh and dried mango was placed in 90 ml of sterile 0.1% peptone water (Merck SAAR4943300DN). It was homogenized for 10 minutes in a zip-lock bag, 10 ml of sterile peptone was poured into one sterile McCartney bottle labelled 10^{-0} and 9 ml into bottles labelled 10^{-1} to 10^{-4}. A quantity of 1ml of the homogenate was pipetted aseptically, with a sterilized pipette into the 10^{-0} dilution and from it, serial dilutions of 10^{-1} to 10^{-4} were prepared. Aliquots of 0.1ml of each dilution were spread-plated in solidified media on petri dishes (Ntuli *et al.*, 2017). The total bacterial count was enumerated on nutrient agar (Merck HG0000C1), coliforms were enumerated on Violet Red Bile Agar (VBRA) (Merck HG0000C23), while fungal counts were determined on Potato Dextrose Agar (PDA) (Merck HG00C100). The plates were incubated at 28 ºC for 48 hours. Each experiment was replicated three times. A colony counter was used to count the colonies, the count (only 30-300 colonies were counted) was expressed as colony forming units per gram ($CFU.g^{-1}$), and an average was recorded.

4.2.7 Microstructure changes

Samples of fresh and dried mangoes were cut into small pieces (10 mm x 10 mm). The samples were mounted on aluminium double-sided stubs and coated with a fine layer of gold, using a sputter gold coater Quorum, Q150RES (Quorum, UK). The samples were examined with a scanning electron microscope (SEM), Zeiss Evo LS15 (Zeiss, Germany). Micrographs were taken at a magnification of 300, 500 and 750 at high vacuum and at an accelerating voltage of 5kV. To enable viewing in high vacuum fresh mango samples had to be prepared, using the standard SEM procedure. The fresh mangoes were washed in 3% buffered Glutaraldehyde for one to three hours, to maintain the structural details. The samples were cleaned in Sodium cacodylate buffer for five minutes. The sample was placed in 2% buffered Osimium Tetraoxide for an hour and cleaned afterwards. Sample dehydration was done by dipping the sample in 10%, 30%, 50%, 70% and 90% ethanol for 10 minutes and in absolute ethanol for 30 minutes. Critical point drying was done prior to the exposure of sample to a high vacuum environment. The process involved the transfer of samples to CPD (critical point drying) baskets under absolute ethanol. During the CPD, the ethanol is replaced with liquid CO_2. It was heated and pressurised to its critical point. The liquid was converted to gas without the damaging effects of surface tension to the sample, resulting in a dry, intact samples.

4.3 Results and Discussions

4.3.1 Fresh mango quality properties

Fresh mangoes were sorted according to the firmness and TSS and mangoes with similar properties were used for the drying experiments. The firmness and TSS were also used as a measure of the maturity of the mangoes used for the drying experiments (Jah *et al*., 2006). The TSS of the fresh mango varied between 10.1-17.1˚Brix with a mean of 13.85˚Brix (Table 4.1). According to Jha *et al.* (2006) ripe mango has a TSS range of 12-23˚Brix and Tommy Atkin mangoes with a TSS range of 12-15˚Brix is considered ripe (Belayneh, 2004; Ahmed and Ahmed 2014). The mangoes used for the drying experiments had a firmness varying between 1.441 N and 12.37 N. The average firmness (4.4 N), as shown in Table 4.1, indicate that the mangoes were ripe (Pleguezuelo *et al*., 2012). Therefore, the TSS and firmness values of the mango used for the drying experiments show that they were of process grade (Kader, 2008).

Table 4.1 Fresh mangoes quality parameters

	Firmness (N)	**TSS (˚Brix)**
Mean values	4.4±3.2	13.85±2.07
CV%	74	13.5
LSD(P>0.05)	3.17	5.19
P	0.81	0.34

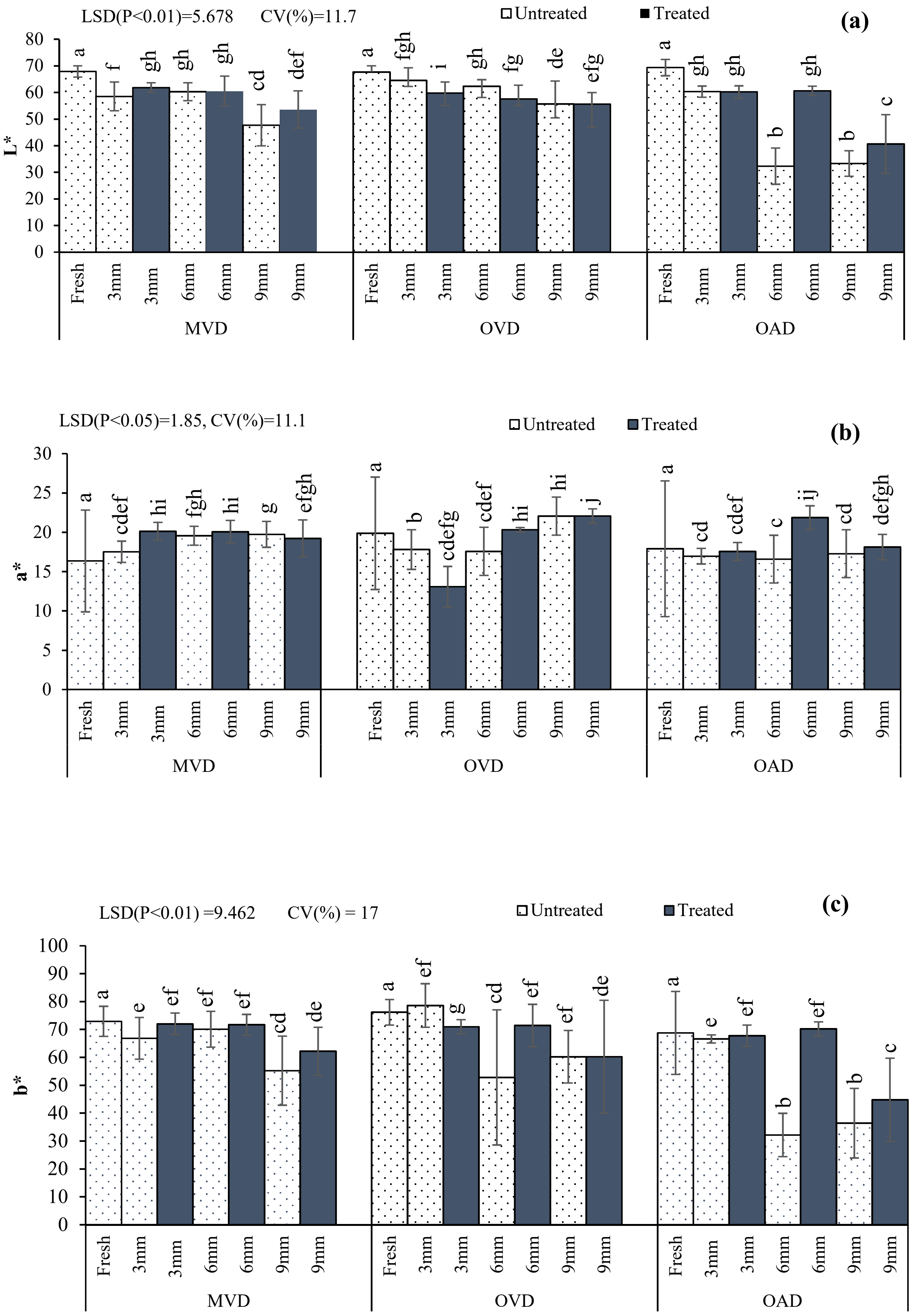
4.3.2 Colour changes

Colour is an important quality parameter used as a measure for market value of produce. Colour was analysed by L*(lightness of colour), a*(degree of redness), b*(yellowness), hue angle, colour change. Studies have indicated that L*, a*, hue angle, change in colour and browning index are the important parameters in colour analysis of dried fruit (Pathare *et al.*, 2013). It was found that the mean L* varied between 69.34 and 67.70 for fresh fruit, 47.68 and 60.28 for MVD dried mango slices , 55.63 and 64.57 for OVD dried mango slices, 32.33 and 60.31 for OAD dried mango slices. It was observed that the lightness of the dried mango slices was relatively lower than the fresh mango lightness, as shown in Figure 4.1-a. There was a highly significant difference ($P<0.001$) in the lightness of mango dried in the three drying methods. It was observed that for all drying methods, thickness had a highly significant effect ($P<0.001$) on the lightness of the mangoes. Furthermore, there was a significantly higher ($P<0.001$) lightness in 3 mm thick slices than 6 mm and 9 mm slices dried in all drying methods. The slices dried in the OVD had a significantly higher ($P<0.001$) lightness than those in the MVD and OAD, respectively. However, lemon juice treatment did not have a significant ($P\geq0.05$) effect on the lightness of the dried mango.

Similar observations were made by Rasouli *et al.* (2011), who observed that there was a decrease in the lightness (L*) of fresh product during drying and that the slice thickness is a factor that has a significant impact on the thicker slices being darker. Ali *et al.* (2016) observed that the OAD results in lower lightness, as compared to the fresh mangoes. The prolonged drying time in OAD and the exposure to oxygen-filled air the reason for the lower lightness values (Ali *et al.*, 2016). Furthermore, de Medeiros *et al.* (2016) also found that pre-treatment does not significantly change the lightness of dried mango. The effect of the drying method*thickness*treatment on redness (a*) was significant ($P<0.05$). However, the redness (a*) was not significantly different ($P>0.05$) among the drying methods. A highly significant ($P<0.001$) difference in redness was observed for the mango slices of different thicknesses. However, the lemon juice treatment did not significantly ($P>0.05$) affect the redness of the mangoes. The mean redness value observed for the control and lemon juice treated 3 mm samples was 17.52-20.12 for MVD, 13.08-17.81 for OVD and 16.97-17.57 for OAD, respectively. The lemon juice treated and control mango slices of 6 mm thickness had a redness variation between 19.56 and 20.07 for MVD, 22.37-17.58 for OVD and 16.59-21.87 for OAD.

The lemon juice treated and control mango slices of the 9 mm thickness had redness values that varied from 19.74-19.22 for MVD, 20.39-22.37 for OVD and 17.28-18.97 for OAD. The redness of the mangoes dried in OAD was not significantly (P>0.05) higher than for the MVD and OAD dried mangoes, respectively. Observations also indicate that there is non-significant difference in the redness between dried and fresh mangoes.

Studies show that drying reduces the yellowness of produce (b*) as observed in Figures 4.1-b and 4.1-c (Shi *et al.*, 1999; Kerkhofs *et al.*, 2005; Akoy, 2014). The hue angle varied from 65.74 to 78.43, indicating the overall yellowness of the sample (Barreiro *et al.*, 1997). This study shows a highly significant (P<0.001) decrease in hue for all drying method. However, the preservation of yellowness was by the OVD (78.43-70.35) and MVD (74.72-71) and a relatively higher reduction in the hue of fresh mango was observed for mango slices dried in OAD. The higher temperatures experienced in the OVD and MVD methods reduced the drying time. Previous research studies showed that drying time is the main factor resulting in preservation of the yellowness of a product (Oliveria *et al.*, 2015). Furthermore, the total colour change (ΔE), which is a combination of L*, a* and b* values, as shown in Appendix 4.1, shows that the highest colour change was for the OAD control samples and the 9 mm dried slices. In addition, the 9 mm control samples dried in the MVD showed a relatively high colour change. This study substantiates other studies (Akoy *et al*., 2014, Oliveria *et al*., 2015), which indicated that drying in higher temperatures such as 70°C result in lower colour change, because of a shorted drying period. The major cause of colour change during drying is carotenoid degradation, maillard reaction and non-enzymatic browning and they are affected by longer drying periods, as in the OVD.



LSD(P<0.01)=5.678 CV(%)=11.7
Untreated
Treated
(a)
L*
MVD
OVD
OAD
LSD(P<0.05)=1.85, CV(%)=11.1
(b)
a*
LSD(P<0.01) =9.462 CV(%) = 17
(c)
b*
Fresh
3mm
6mm
9mm

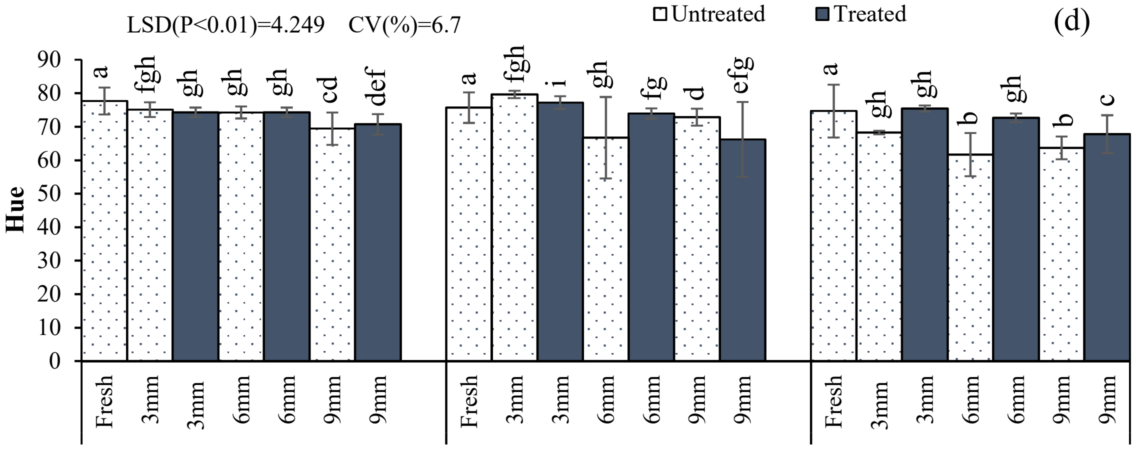


Figure 4.1 Variation of colour parameters L*(a), a*(b), b*(c) and hue (d) for the fresh and dried mangoes

4.3.3 Rehydration characteristics

Rehydration properties are quality criteria that serve to indicate the physical and chemical changes that occur during drying (Abano *et al.*, 2013). The rehydration ratio and rehydration coefficient of the mango slices dried by the OVD, MVD and OAD methods were not significantly (P>0.05) different, as shown in Table 4.2. The rehydration ratio for samples dried by OVD was between 2.518±0.43 and 1.512±0.28, for MVD it varied between 2.542±0.29 and 1.591±0.09 for OAD it was between 2.667±0.05 and 1.649±0.06. The OVD dried mango had a relatively higher rehydration rates, compared to those dried by the MVD and OAD methods. It was also observed that, the rehydration ratio was significantly higher (P<0.001) for 3 mm than the 6 mm and 9 mm mango slices dried using the three methods. Pre-treatment did not affect the rehydration of mango slices significantly (P>0.05). Abano and Sam-Amoah (2011) and Abano *et al*. (2013) also concluded that the rehydration characteristics of bananas and mangoes are not affected by pre-drying treatments. The rehydration coefficient coincide with that of Askari *et al.* (2006) who found a coefficient of 0.405 for hot air drying. The highest rehydration ratio in OAD is attributed to higher internal stresses during drying (Kathirvel *et al*., 2006). Slice thickness is one of the factors that influences the rehydration characteristics (Madamba, 2003). A relatively higher rehydration ratio in 3 mm slices indicates that there was no cell wall damage for the thinner dried mangoes (Sacilik e*t al.,* 2006). Perumal (2007) observed that the rehydration ratio for thinner slices is relatively higher, when drying tomatoes.

A lower rehydration ratio of the 6 mm and 9 mm dried mango slices also indicates there is a denaturing of proteins and cell wall damage (Perumal, 2007).

Table 4.2 Rehydration ratio of dried mango samples

Drying method	**Treatment**	**Thickness(mm)**	**Rehydration ratio (dimensionless)**	**Rehydration coefficient (dimensionless)**
OVD	Lemon juice treatment	3	2.518±0.43e^{ghi}	0.5105±0.01^{efghi}
		6	1.986±0.13^{bcdefg}	0.4413±0.03^{bcdefg}
		9	1.152±0.28^{a}	0.2561±0.03^{a}
	Control	3	2.297±0.25^{fghi}	0.5595±0.06^{ghi}
		6	2.107±0.17^{cdefgh}	0.4667±0.03^{cdefgh}
		9	1.479±0.25^{ab}	0.3288±0.03^{ab}
MVD	Lemon juice treatment	3	1.919±0.18^{bcdef}	0.4265±0.04^{bcdef}
		6	2.352±0.06^{fghi}	0.5222±0.07^{fghi}
		9	1.591±0.09^{abc}	0.3536±0.02^{abc}
	Control	3	2.100±0.05^{cdefgh}	0.4682±0.06^{cdefgh}
		6	2.542±0.29^{hi}	0.5649±0.01^{hi}
		9	1.718±0.26^{bcd}	0.3817±0.04^{bcd}
OAD	Lemon juice treatment	3	2.518±0.18^{ghi}	0.5597±0.02^{ghi}
		6	1.649±0.06^{abcd}	0.3664±0.03^{abcd}
		9	1.756±0.09^{bcde}	0.3901±0.05^{bcde}
	Control	3	2.667±0.05^{i}	0.5926±0.06^{i}
		6	2.171±0.29^{defghi}	0.4825±0.04^{defghi}
		9	1.861±0.26^{bcdef}	0.4136±0.04^{bcdef}
CV%			14.1	14.1
LSD (P=0.05)			0.475	0.106
P			0.851	0.851

*Mean values (±SD) with similar superscript letters in a column are not significantly different (p<0.05)

4.3.4 Sensory quality results

A sensory determined flavour, colour and overall acceptability of lemon juice treated and control mangoes of various thicknesses. There was a highly significant (P<0.001) difference in the consumer acceptability of the colour of the lemon juice treated and the control mango slices dried by the three methods used. The lowest acceptability was for the control mango slices dried using OAD (4.327±2.17). It was found that the panellists liked the colour of lemon juice treated mango slices dried using MVD (7.000±1.19) than the OVD (6.923±1.17) and OAD (6.635±1.79) dried mangoes.

The difference in the likeness of the flavour of the dried mango was highly significant ($P<0.001$), as shown in Table 4.3. The panellists liked the flavour of the lemon juice treated mango slices dried in MVD (6.827±1.37) than those dried in OVD (6.788±2.02) and OAD (6.442±2.02). Furthermore, the panellists did not like the colour of the control dried mango slices dried in OAD because of the visible browning colour. In addition, mango slices dried in the MVD and OVD had the highest overall acceptability, as shown in Table 4.3. The overall acceptability of mango slices dried in MVD was significantly ($p<0.001$). The study findings show the overall acceptability for lemon juice treated mango dried in MVD was the highest. Similar observations made by Abano *et al.* (2013) show that lemon juice pre-treatment has an influence on the panellists scoring of flavour, colour and overall acceptability of dried mango. In addition, Masamba *et al.* (2013) also found that mango pre-treated with lemon juice had higher scores of colour and flavour acceptability compared to control samples.

Table 4.3 Consumer acceptability of treated and untreated dried mango of varied thickness

Drying method	**Treatment**	**Flavour**	**Colour**	**Overall acceptability**
OVD	Lemon juice treatment	6.788 ± 2.02^{b}	6.923 ± 1.17^{b}	6.941 ± 1.64^{c}
	Control	6.115 ± 1.94^{b}	6.538 ± 1.88^{b}	6.010 ± 1.79^{b}
MVD	Lemon juice treatment	6.827 ± 1.37^{b}	7.000 ± 1.19^{b}	7.088 ± 1.26^{c}
	Control	6.538 ± 1.95^{b}	6.500 ± 1.73^{b}	6.343 ± 1.69^{bc}
OAD	Lemon juice treatment	6.442 ± 2.02^{b}	$6.635\pm1.79.^{b}$	6.510 ± 2.07^{bc}
	Control	5.269 ± 1.99^{a}	4.327 ± 2.17^{a}	5.00 ± 1.95^{a}
LSD		0.717	0.660	0.690
CV%		29.3	27.1	28.0
P		0.001	0.001	0.001

*Mean values (±SD) with similar superscript letters in a column are not significantly different ($p<0.05$)

4.3.5 Microbial load and safety results

The lower moisture content and water activity of dried fruit has led to the fruit being viewed microbiologically safe (FAO/WHO, 2016). However, the increased levels of food-borne illness have increased the concerns about the microbial quality of low moisture content foods (de Sausa, 2008; FAO/WHO, 2016). The microbial load is shown in Table 4.4 for OVD, OAD, and MVD dried mango slices. The lemon juice treated and control mango slices contained fungi and anaerobic bacteria only. Fungal counts varied between $3\pm1x10^7$ and $7\pm7.5\ x10^7$ $CFU.g^{-1}$ for the lemon juice treated dried mango slices, for the control dried mango slices the mean fungal counts varied from $5\pm5.8x10^7$ to $2\pm1.4x10^8$ $CFU.g^{-1}$. The mean Total Anaerobic Counts (TAC) varied from $7\pm2.5\ x10^7$ to $5\pm2.4\ x10^7$ $CFU.g^{-1}$ for the lemon juice treated dried mango slices, while the control dried mango slices had a TAC count of about $8\pm3.7\ x10^7$ $CFU.g^{-1}$. The pre-drying treatments and drying methods used did not significantly ($P>0.05$) both fungal counts and TAC. The lowest TAC observed was for the lemon juice treated mangoes dried by OAD and MVD, respectively, and the highest was for control mangoes dried by OVD. The absence of faecal coliforms in dried mango is an indication of safety of the dried mangoes for human consumption, as there are no pathogenic micro-organisms (ICMSF, 1982). It also indicates good hygienic and handling practices (Ntuli *et al.,* 2017).

The fungal counts and TAC obtained in dried mango were above the World Health Organisation standards. A guideline by Gilbert *et al.* (2000) indicates that a TAC count of less than $1x10^2$ $CFU.g^{-1}$ is acceptable. In addition, the safe limit for fungi is less than $1x10^3$ $CFU.g^{-1}$ (ICMSF, 1982; Wittum *et al*., 2009). However, according to the Health Protection Agency (HPA), the presence of anaerobic bacteria is an indication of a lower quality of the produce and it is not a priority in the safety of products (HPA, 2009). The study findings on the TAC and fungal counts indicate unacceptable microbial quality of the dried fruit. According to Babiker *et al.* (2014), drying should reduce the microbial counts of fungi and anaerobic bacteria. Therefore, the drying temperatures used for the drying experiments might not be sufficient to kill anaerobic bacteria, hence, creating available moisture to support the growth of the micro-organisms (Adu-Gyamfi and Mahami, 2017). Beuchat and Mann (2014) also illustrate that lethal processes are necessary to prevent growth of anaerobic bacteria. Fungi are more prominent in foods that have a high sugar content and they are tolerant to low moisture content foods (Sagar and Suresh, 2010). Furthermore, the sugar content in fruit, such as mangoes enhances the survival of heat resistance micro-organisms (Beuchat *et al*., 2013; Finn et al, 2013). The sugar content of mangoes could be a contributing factor to the high levels of fungi in the lemon juice treated and control slices. These studies are in support with FAO (2004), indicating that modified solar driers are free from microbial contamination and produce better quality products than open-air uncontrolled solar dried products. Several studies on fish and meat drying have also shown that conventional drying methods, such as OVD do not eliminate the growth of anaerobic bacteria and fungi (Adu-Gyamfi and Mahami, 2017; Cherono *et al.*, 2016).

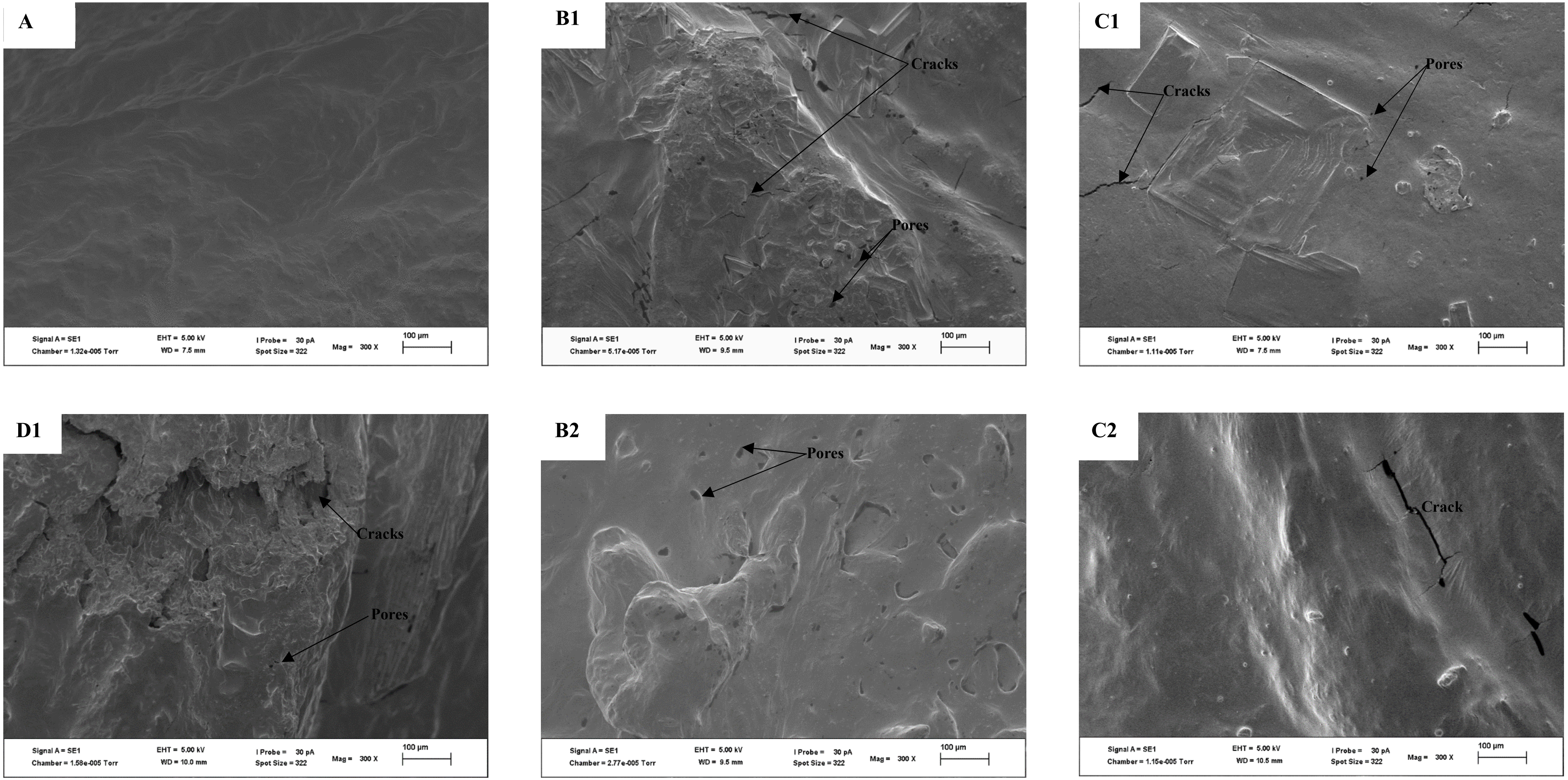
Table 4.4 The microbial counts of dried mango

Drying method	**Treatment**	**VRB ($CFU.g^{-1}$)**	**PDA ($CFU.g^{-1}$)**	**TAC ($CFU.g^{-1}$)**
Fresh mango		ND	ND	ND
OVD	Lemon juice treatment	ND	$7\pm7.5\ x10^{7a}$	$7\pm2.5x10^{7a}$
	Control	ND	$8\pm6.2x10^{7ab}$	$8\pm3.3x10^{7a}$
OAD	Lemon juice treatment	ND	$7\pm6.4x10^{7a}$	$5\pm\ 2.4x10^{7a}$
	Control	ND	$2\pm1.4\ x10^{8b}$	$8\pm3.3x10^{7a}$
MVD	Lemon juice treated	ND	$3\pm1x10^{7a}$	$5\pm2.4\ x10^{7a}$
	Control	ND	$5\pm5.8x10^{7a}$	$8\pm3.7\ x10^{7a}$
P>0.05		-	0.289	0.682
LSD		-	$1\ x10^{8}$	$4\ x10^{7}$
CV (%)		-	108.9	48.2

*Mean values (±SD) with similar superscript letters in a column are not significantly different ($p<0.05$), ND=not detected

4.3.6 Changes in the microstructure of mango slices

Scanning Electronic Microscopy (SEM) was used for comparing the surface microstructure of fresh and dried mango slices, using SEM micrographs, as shown in Figure 4.5. Fresh mangoes showed a smooth irregular surface. There was no clear difference in observations made for treated and untreated mango slices dried in MVD, OVD and OAD. There was evidence of microstructural difference for the 3 mm, 6 mm and 9 mm dried mango slices. Furthermore, observations showed that the 3 mm slices form a regular surface with pores and cracks as shown in Figure 4.5 (B1, C1 and D1). Cracking was mainly observed for 3 mm, 6 mm and 9 mm mango slices dried in OAD, as shown in Figure 4.5 (D1-D3). Fazaeli *et al.* (2012) also indicated that samples dried, using hot air become porous. This is a result of water evaporation from the samples. The formation of cracks is a clear indication of cell wall damage, which is caused by a long drying time (Lewicki and Pawlack, 2003; Vega-Galvez *et al.*, 2012). The observation made by López *et al.* (2016) show that most of the drying methods damage the microstructure of the fruit. However, significant damage is observed for open-air uncontrolled drying. This could be a result of the exposure of the fruit surface to outside air conditions, for a longer period.


A
B1
Cracks
Pores
C1
Cracks
Pores
D1
Cracks
Pores
B2
Pores
C2
Crack
100 µm

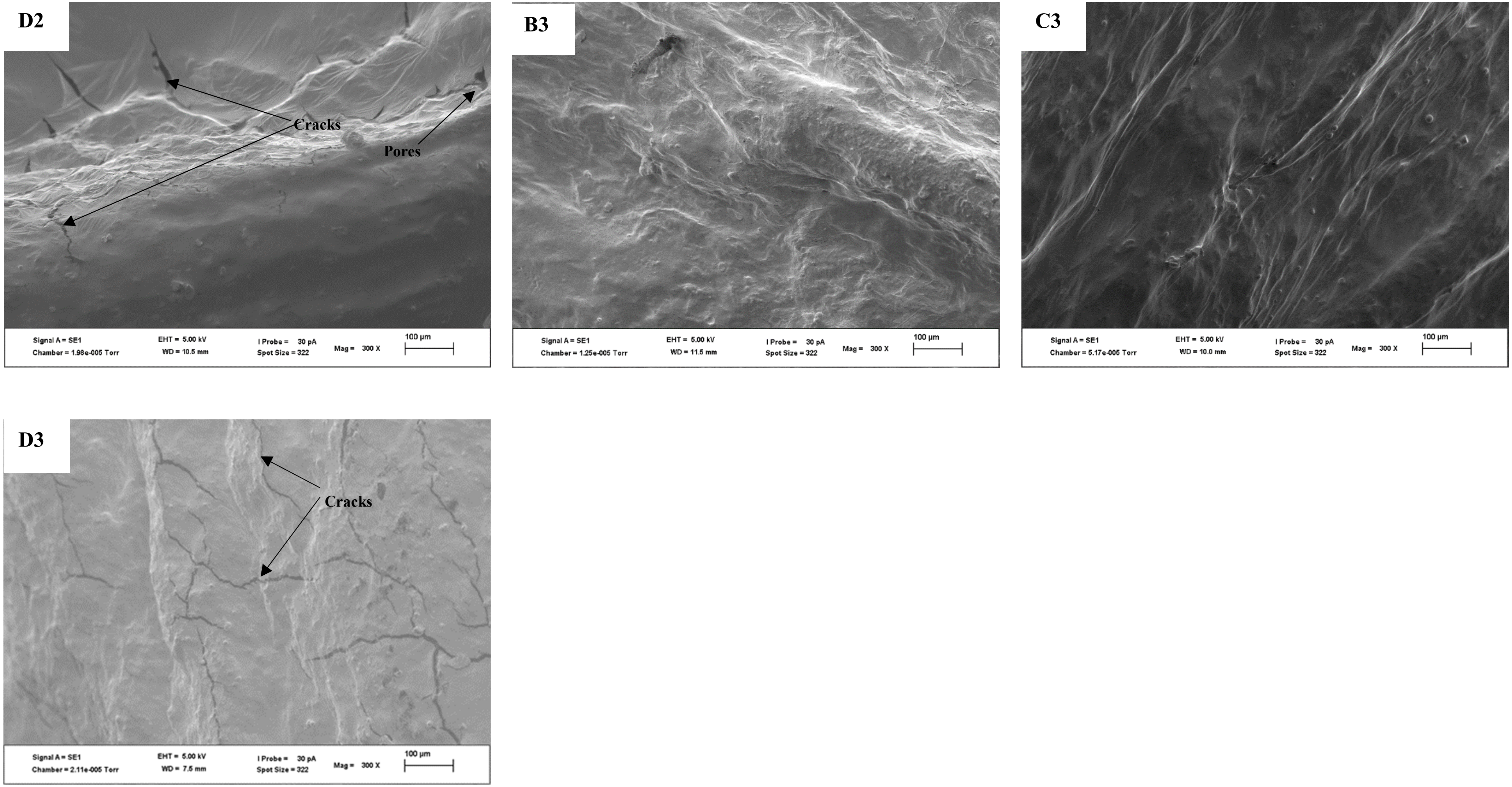


Figure 4.2 Figure 15 SEM micrographs of (A1) fresh mango; (B1, B2, B3) 3mm, 6mm and 9mm mango slice dried in MVD; (C1, C2, C3) 3 mm, 6 mm and 9 mm mango slice dried in OVD; (D1, D2, D3) 3 mm, 6 mm and 9 mm mango slice dried in OAD (300 x magnification, 100 µm scale)

4.3.7 Conclusions

Hot air methods used for the drying experiments had an influence on the quality characteristics mangoes. OAD dried produce was characterised by a higher colour change (ΔE), a lower overall consumer acceptance, relatively higher rehydration ratio, higher TAC and fungal count and the significant damage of product cell wall. MVD was observed to be an effective method of drying, which has the potential to replace the convective oven drying method because, similar observations were made on the results of quality properties investigated in the study. This study also found that lemon juice pre-treatment does not significantly ($P>0.05$) affect the quality of dried mango. The main factor influencing the quality is drying temperature, which influenced the drying time. The exposure of fruit to hot air for longer drying periods has been shown to have an effect on the quality of the fruit. The mango slices dried in OVD took a relatively shorter drying period, as a result the quality of mangoes was preserved, compared to that of the mangoes dried in MVD and OAD, respectively. Considering the current shift in South Africa to promote renewable energy sources, it is recommended that a solar collector be included in the MVD, to further increase the drying temperature for reduction of the drying time. This will also reduce the growth of anaerobic bacteria. Although the dried mango is acceptable for human consumption, it is necessary to investigate other possible pre-treatments that could potentially create an environment that does not promote fungal growth, during drying of mangoes. A mango slice thickness of 3 mm or 6 mm is more suitable for drying, because it takes a relatively shorter time to dry, resulting in less cell damage and better quality retention.

4.3.8 References

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5. CONCLUSIONS AND RECOMMENDATIONS

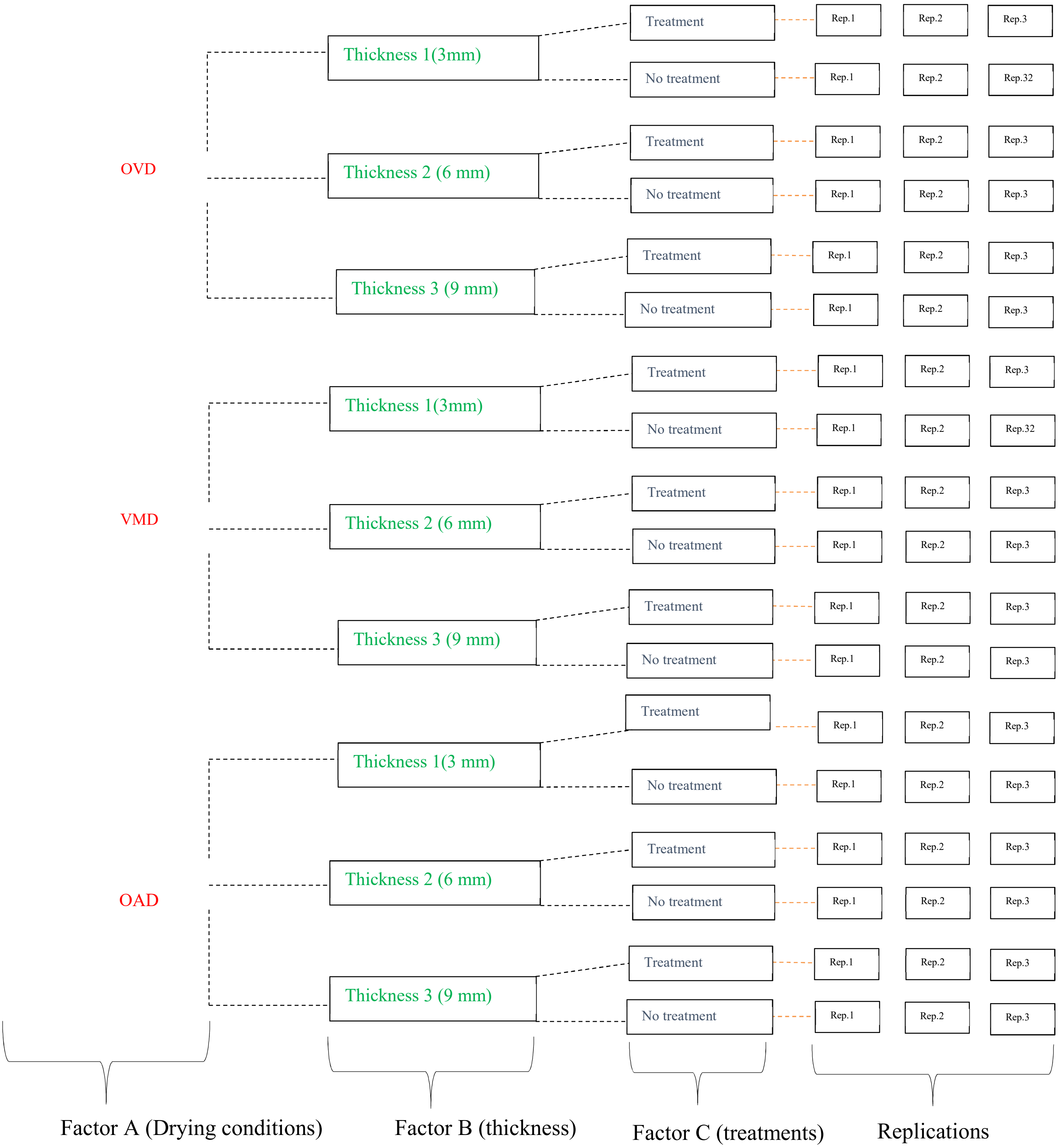
Mango is a seasonal fruit, and in South Africa 75% of the fruit is produced in the Limpopo. The recent consumer preference for healthy snacks has created a demand for the dried mango fruit. Smallholder farmers producing mangoes experience relatively high post-harvest losses of up to 50%. The reduction of the post-harvest losses is a sustainable measure that can be implemented for smallholder farmers, to penetrate the market through selling value added produce. The demand for dried mangoes, coupled with their high value in South Africa, makes drying an attractive solution for smallholder farmers to establish businesses and sell dried fruit, specifically during the off-season of mango. This practice can potentially increase the availability of mango throughout the country. The literature studies showed that hot air drying is the simplest applicable drying method, in terms of cost and the ability to dry a wide range of produce. The study experimented with three hot air drying methods, namely, a convective oven dryer (OVD), open-air uncontrolled solar drying (OAD) and a modified ventilation solar dryer, using a greenhouse (MVD). The three hot air drying methods were compared and their effect was observed on 3 mm, 6 mm and 9 mm mango slices that had been pre-treated with lemon juice and samples that were not treated (control).

OVD drying was done at a set temperature of 70˚C, OAD at an ambient temperature of 15.55˚C- 36.77˚C, RH of 22.96%-79% and an average solar radiation of 769 $W.m^{-2}$ and MVD improved the ambient conditions to an average maximum of 64.26˚C and the relative humidity of 17.6%. The weather conditions used for solar drying were within an acceptable range. However, the ambient air had a relatively high relative humidity, which resulted in a longer drying period for OAD. The study observations indicate that mangoes dried using OVD dried faster than those dried in MVD and OAD. The maximum drying rate in OVD (0.33$g.hr^{1}$) was 3% higher than MVD (0.2 $g.hr^{-1}$) and 12% higher than OAD (0.12 $g.hr^{-1}$). The lowest drying rates were for 9 mm mango slices while the highest were for 3 mm mango slices. The lemon juice pre-treatment did not affect the drying rate for all drying methods and all mango slice thicknesses dried. Furthermore, increased drying rates in OVD and MVD resulted in a shorter drying time for 3 mm and 6 mm mango slices and most of the drying took place in the falling drying rate period, which indicates that the main drying mechanism was diffusion. The lemon juice treatment did not significantly affect diffusivity, although the samples had a relatively higher moisture diffusivity, while only the thickness had a significant effect on moisture diffusivity. Research studies clearly indicate that where the drying mechanisms are capillary and gravitational forces, as in the constant drying rate period the result will be damage to the surface of the product. This was observed in microstructure of 9mm mango dried in OAD. The Midilli *et al.* and Page models were the best fit for drying data and were useful for modelling the drying moisture ratio of mangoes. Sensory evaluation studies indicates that 3 mm lemon juice treated mango slices dried in MVD was preferred, in terms of colour, flavour and overall acceptability and, for all drying methods 9 mm dried mango slices were the least preferred. EMS and rehydration rates showed the structural changes, which occurred, during drying. A relatively higher structural damage was observed for the 9 mm dried mango slices, which also showed more cracks that are visible on the micrographs. The relatively lower rehydration rate and the observed structural changes can be attributed to the longer drying periods. This was observed for 9 mm thick dried mango slices and mostly mango dried in the OAD. In addition, the total colour change (ΔE) was relatively higher for samples dried in OAD, showing the browning of the mango slices.

MVD is a practical drying method recommended for implementation in South African conditions. It dries the mango fruit within an acceptable drying period, compared to OAD and the drying kinetics are almost similar to those of a convective oven dryer (OVD). The MVD needs to be developed further, by developing methods, such as the use of solar thermal collectors and air recirculation to increase the temperature, in order to reduce the drying time. This study recommends that further studies include an investigation into the air dynamics within the MVD, for further modification of the ventilation system. Furthermore, to promote the solar drying technologies manuals of standards of design, orientation and operation for the MVD and other solar drying technologies can be drafted. The optimum thicknesses of mango slices used in drying is 3 mm and 6mm, because they have a shorter drying time and hence allow for the preservation of the quality of the mangoes. This study recommends further investigation into pre-treatments, which will increase the drying rates, for further reduction of the drying time. Further investigations into the drying method, therefore, need to identify the type of fungi and aerobic bacteria and conduct a microbial analysis on an hourly interval, during the drying process, in order to identify the critical point, where the of anaerobic bacteria and fungi starts to grow. This study also recommends, for the engineering designs to identify methodologies that will consider the selection of food-safe material and other food safety components. Furthermore, it is also recommended to develop microbial count limit standards, which are applicable for the South African drying industry. Lastly, further studies can investigate the shelf-life of dried mangoes and the payback period of MVD.

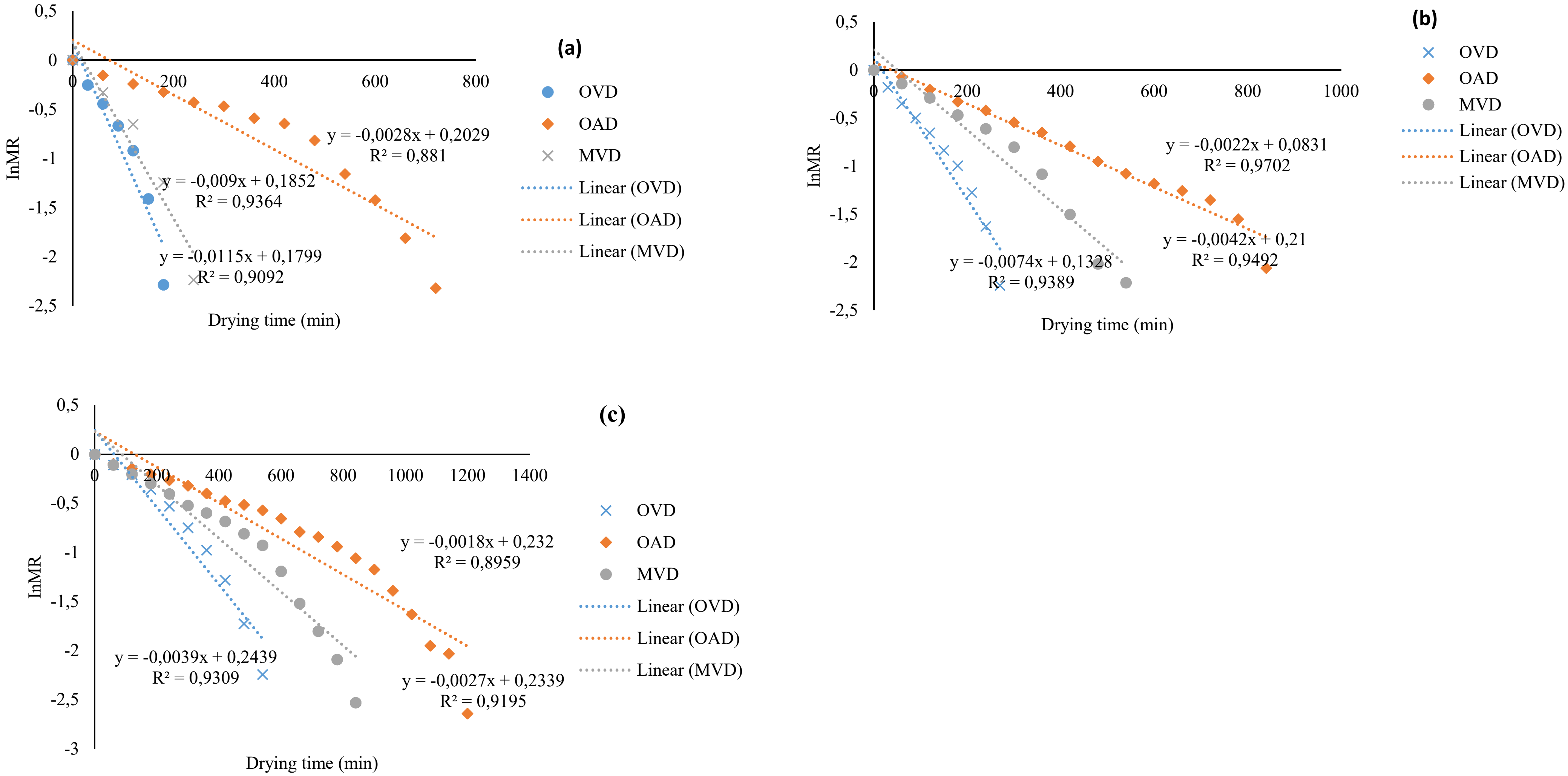
6. APPENDICES

6.1 Appendix 3.1: Experimental Design

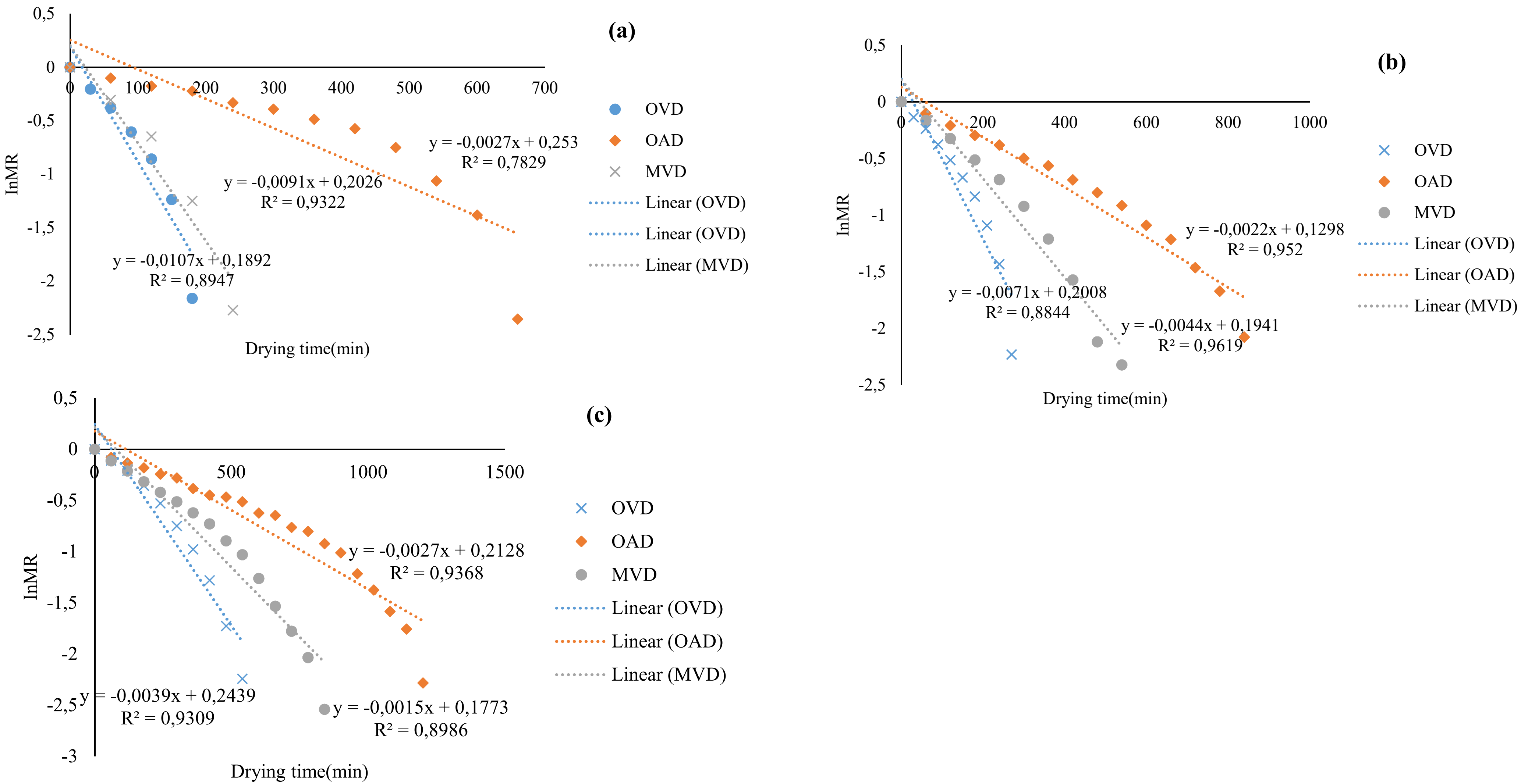


6.2 Appendix 3.2: Effective Moisture Diffusivity Linear Curves

Effective moisture diffusivity curves for untreated dried mango of (a) 3mm, (b) 6mm and (c) 9mm thickness



Effective moisture diffusivity linear curves for treated dried mango of (a) 3mm, (b) 6mm and (c) 9mm thickness



6.3 Appendix 4.1: Table of Total Colour Change

Drying method	Thickness	Treatment	ΔE
MVD	3	Control	11.25505
MVD	3	Lemon juice treated	7.205167
MVD	6	Control	8.733829
MVD	6	Lemon juice treated	8.33576
MVD	9	Control	27.07443
MVD	9	Lemon juice treated	18.11597
OVD	3	Control	4.47313
OVD	3	Lemon juice treated	11.69546
OVD	6	Control	24.08822
OVD	6	Lemon juice treated	11.17621
OVD	9	Control	20.12379
OVD	9	Lemon juice treated	18.5591
OAD	3	Control	9.3404
OAD	3	Lemon juice treated	9.184075
OAD	6	Control	52.07166
OAD	6	Lemon juice treated	9.677768
OAD	9	Control	48.4267
OAD	9	Lemon juice treated	37.4026

6.4 Appendix 4.2: Sensory Evaluation sheet

Panellist name:

Instructions:

i. Rinse your month with the water before tasting a sample (including the first sample)
ii. Rate your liking of mouth feel, colour and overall acceptability for each coded sample using the scale in the next page

Sample code	Flavour/mouth feel	Colour	Overall Acceptability
442			
276			
785			
431			
635			
327			

Dried mango Scoring Guidelines

Please score dried mango samples using the following scale

Score		Flavour	Colour	Overall acceptability
1	Extremely dislike	Extremely poor	Extremely poor	Extremely poor
2	Dislike very much	Very poor	Very poor	Very poor
3	Dislike moderately	Poor	Poor	Poor
4	Dislike slightly	Below fair/above poor	Below fair/above poor	Below fair/above poor
5	Neither like nor dislike	Fair	Fair	Fair
6	Like slightly	Below good/above fair	Below good/above fair	Below good/above fair
7	Like moderately	Good	Good	Good
8	Like very much	Very good	Very good	Very good
9	Like extremely	Extremely good	Extremely good	Extremely good

6.5 Appendix 4.3: Ethics Approval Certificate

UNIVERSITY OF KWAZULU-NATAL™

INYUVESI YAKWAZULU-NATALI

25 July 2017

Ms Khuthadzo Mugodo 208501527
School of Engineering
Howard College Campus

Dear Ms Mugodo

Protocol Reference Number: HSS/0307/017M
Project title: Evaluation of three drying methods and the effect on thin layer drying of Tommy Atkin Mango

Full Approval – Expedited Application

In response to your application received 3 April 2017, the Humanities & Social Sciences Research Ethics Committee has considered the abovementioned application and the protocol has been granted **FULL APPROVAL.**

Any alteration/s to the approved research protocol i.e. Questionnaire/Interview Schedule, Informed Consent Form, Title of the Project, Location of the Study, Research Approach and Methods must be reviewed and approved through the amendment /modification prior to its implementation. In case you have further queries, please quote the above reference number.

PLEASE NOTE: Research data should be securely stored in the discipline/department for a period of 5 years.

The ethical clearance certificate is only valid for a period of 3 years from the date of issue. Thereafter Recertification must be applied for on an annual basis.

I take this opportunity of wishing you everything of the best with your study.

Yours faithfully

....

Dr Shenuka Singh (Chair)
Humanities & Social Sciences Research Ethics Committee

/pm

cc Supervisor: Dr TS Workneh & Mr Sipho Sibanda
cc. Academic Leader Research: Prof Christina Trois
cc. School Administrator: Ms Nombuso Dlamini

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